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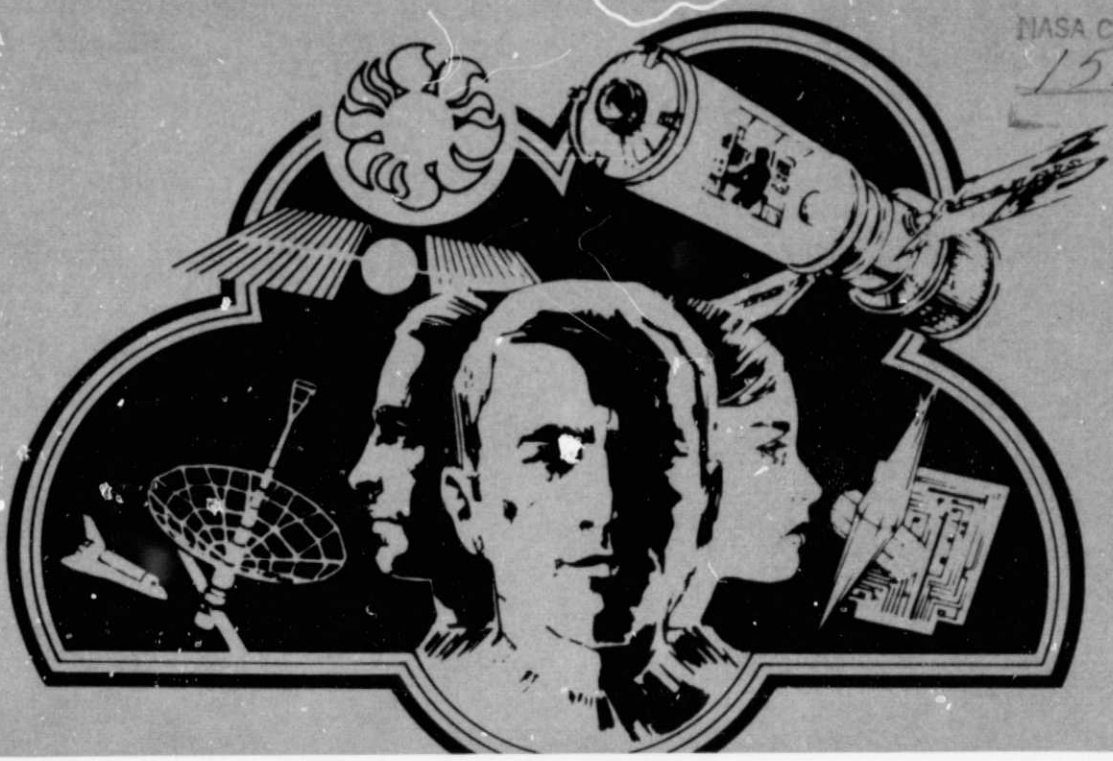

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# SPACE STATION SYSTEMS ANALYSIS STUDY
# PART 3: DOCUMENTATION

## VOLUME 1
## Executive Summary

MCDONNELL DOUGLAS ASTRONAUTICS COMPANY

CONTRACT NO. NAS 9-14958
DFD NO. 524
DR NO. MA-04

MCDONNELL DOUGLAS CORPORATION

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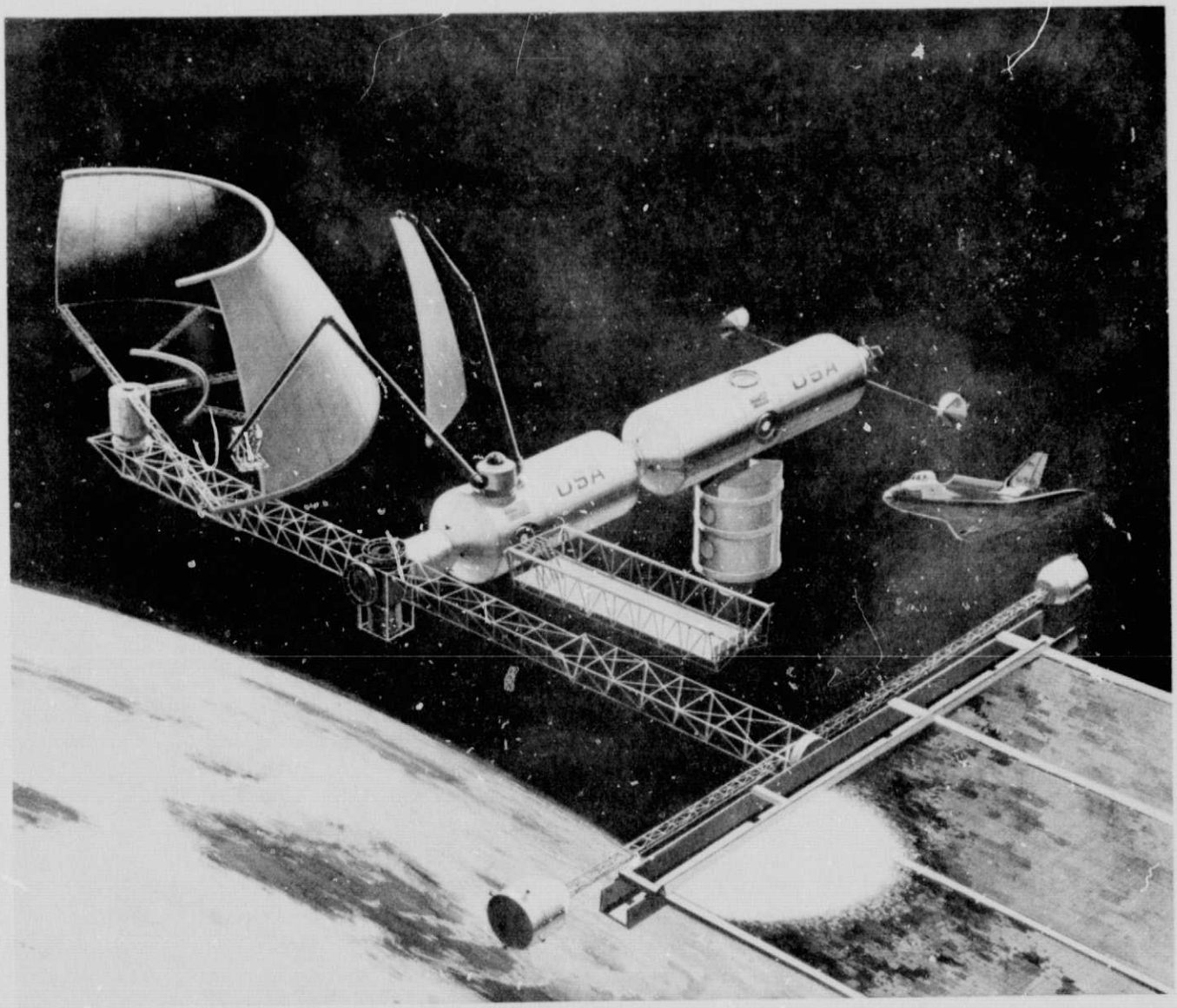

A new era in the exploration and utilization of space will begin as the Shuttle Transportation System becomes operational and the cost and complexity of delivering payloads to space is reduced. Larger living and working quarters will be provided for space crews, thus extending their periods of residency in space beyond that possible in the Orbiter alone. New tools and work stations will be designed to enhance crew productivity. Space construction projects will be undertaken to build large communication antennas, microwave radiometers and solar power systems to serve the needs of our future generations. These space facilities will provide an expanded base for the more traditional scientific endeavors and in addition, laboratory and testing facilities will be developed for manufacturing new materials and products in the unique environment of space.

MCDONNELL DOUGLAS

## PREFACE

The Space Station Systems Analysis Study, summarized in this document, was a 15-month effort (April 1976 to June 1977) to develop a cost-effective space station system concept capable of meeting a broad spectrum of mission requirements and providing orderly growth with regard to both function and orbit location. The study activity has been organized into three parts. Part 1 was a five-month effort to review candidate objectives, define implementation requirements, and examine potential program options for both low earth and geosynchronous orbits. It was completed on 31 August 1976 and was documented in three volumes (report MDC G6508, dated 1 September 1976).

Part 2 of the study (also five months in duration) defined and evaluated specific system options falling within the program options developed in Part 1. This portion of the study was completed on 31 January 1977 and was also documented in three volumes (report MDC G6715, dated 28 February 1977).

The third and last portion of the study (February to June 1977) has analyzed space construction concepts in more depth and has defined a Space Construction Base concept in sufficient detail that preliminary program plans can now be formatted for its implementation.

This volume summarizes the principal issues addressed and the conclusions reached during the study. The companion volumes include the Technical Report (Volume 2), the associated Appendices (Volume 3) which document the analyses and design studies conducted during this last portion of the study, and the Supporting Research and Technology Report (Volume 4).

During the study, subcontract support was provided to the McDonnell Douglas Astronautics Company (MDAC) by TRW Systems Group, Ford Aerospace and Communications Corporation, the Raytheon Company, and Hamilton Standard.

Questions regarding the study activity or the material appearing in this report should be directed to:


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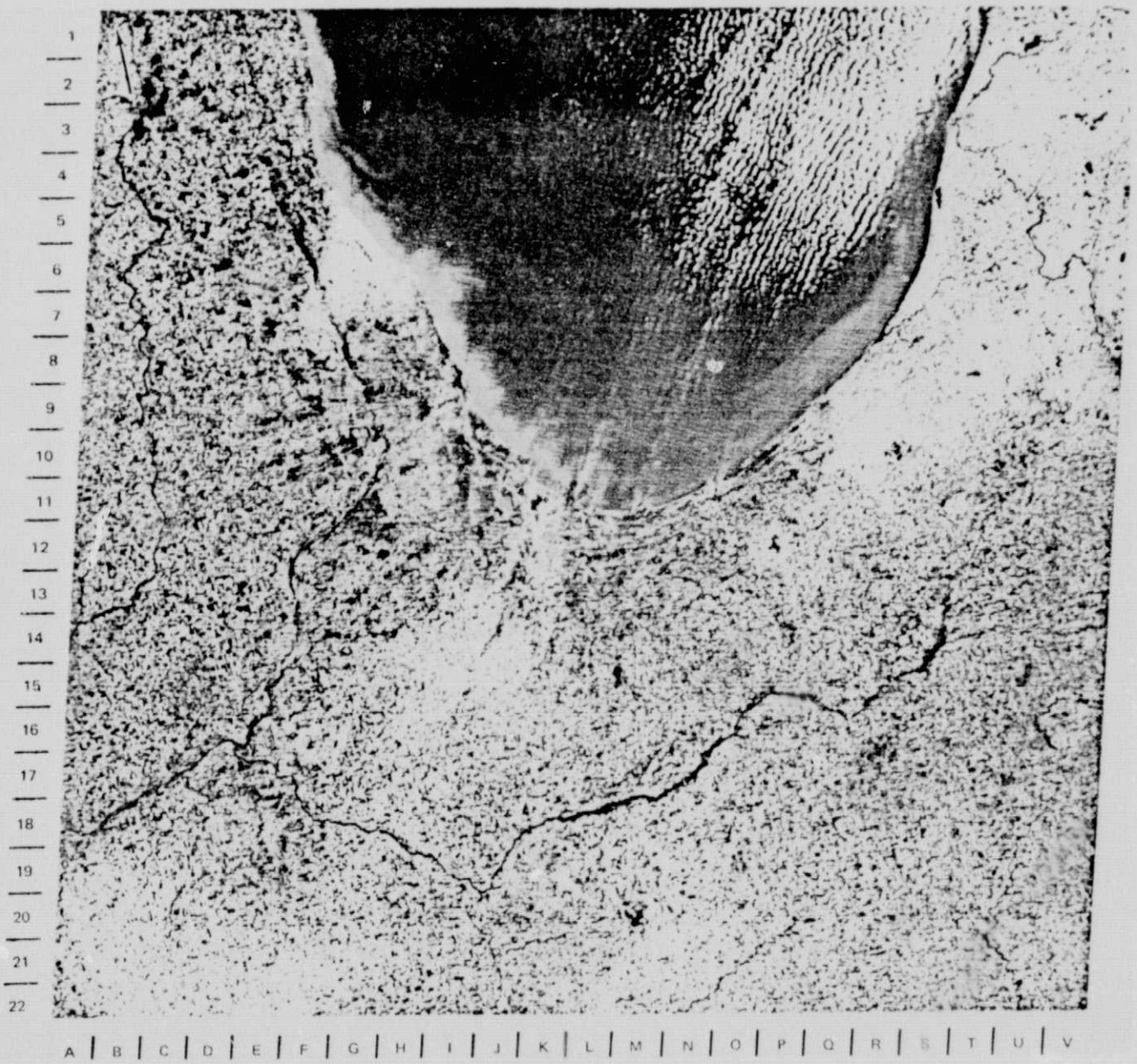


This image from Landsat (1124-16050-November 24, 1972) is typical of the observations of earth possible from space. The area covered by this image includes the cities of Chicago, Hammond, and Gary, Indiana. The Hammond-Gary area is one of the great steelmaking regions of the country. This great concentration of industry has given rise to many environmental problems; for example, the weather around Gary has been significantly altered by the pollution and added heat from the factory area with more cloudy days than the surroundings. Smoke plumes seen heading northeast across Lake Michigan from the Chicago-Hammond-Gary area appear to lead into the lines of clouds over the lake west of St. Joseph and Benton Harbor (S-3), Mich. It has been suggested that the smoke particles serve as condensation nuclei, promoting cloud formation and possibly more snowfall in areas southeast of the lake. Landsat imagery is currently limited to the visible and near-IR region of the spectrum. To expand our base of knowledge of the earth and the atmosphere, corollary information is needed in the microwave region, which in turn establishes the need for large (100m to 300m) microwave radiometers. The size of these radiometers requires that they be constructed in space, an activity that becomes practical with the advent of extended manned missions.

**The excitement and challenge of new ventures, the realization of accomplishments benefiting all of mankind, the technical and scientific achievement necessary to provide a reservoir of knowledge and a firm foundation for future growth – these are the promises and opportunities provided by the Space Program of the United States of America . . .**

## INTRODUCTION

In the past 20 years this nation's investment in space programs has resulted in economic, social, and scientific gains from the services provided by communication satellites and weather satellites; has provided new insights for scientists through the routine operation of earth-surveying satellites and solar observatories; and has permitted us to take the initial steps in planetary exploration. We have even placed man on the lunar surface.

Now, the threshold of a new era is at hand. The reduction in the costs and complexity of delivering payloads to space as provided by the Shuttle Transportion System will mark a new era in the exploration and use of space. When this capability is coupled with the advantages demonstrated in Skylab and Apollo of space crews living and working in space, a mechanism becomes available to investigate, understand, and solve many of the critical problems that we and the rest of the world will face in the next 50 years.

The objective of the study summarized in this document was to develop a cost-effective space station system concept, supported by the Shuttle Transportation System, that is capable of satisfying a broad spectrum of mission requirements while following a logical evolutionary development with regard to function, orbital location, and budgetary realism. The output of the study will provide to NASA program planners information that can be useful in solving the difficult problems of apportioning limited resources among an almost unlimited number of candidate projects – and in so doing, will provide a sound technological base capable of developing and preserving the options open to our nation in the decades to come.

Many space station studies and mission definition studies have been sponsored by NASA during the last 20 years and these earlier studies were used in establishing the point of departure for the present effort. The principal difference between the present study and those conducted previously is in the theme set for the space operations of the future. In previous studies, a laboratory-in-space perhaps best describes the approach taken in conceptualizing the next generation of manned space missions. Emphasis previously was placed on the concept of a basic research facility. In the current study, perhaps stimulated in part by the innovative concepts of G. K. O'Neill and Peter Glaser, the theme has been the utilization of space. Areas examined included space construction requirements for large solar power systems and large communications antennas, platforms for earth services, manufacturing or processing facilities for hard goods and pharmaceuticals, facilities for proof-of-concept testing for pilot manufacturing plants in space, as well as the providing of a base for the more traditional scientific research endeavors.

The Space Station Systems Analysis Study has been a 15-month effort organized into three consecutive 5-month periods of work. The first period concentrated on the selection of objectives, iden-

tification of mission hardware, description of program options, and the identification of program requirements. The second period concentrated upon the further definition of the most promising program options, definition of mission hardware, and the development of space construction concepts and configurations as well as system requirements. The third portion of the study focused on the analysis of specific construction systems and the development of an evolutionary program featuring a sequential growth of manned operations from Shuttle/Sortie support missions, advancing to Shuttle-tended missions, and eventually transitioning to continuously manned facilities capable of supporting large construction projects and other space activities.

In achieving the study goals while following a logical evolutionary development path that does not overstep the bounds of responsible fiscal management, numerous issues were examined. The issues were phrased in the form of questions for which answers were sought. The following principal questions were considered:

- Toward what key objectives should space station systems be directed during the remainder of this century?
- What requirements do these key objectives place on space systems?
- Is there a common point of departure in developing a program plan with the flexibility and growth potential to meet these objectives?
- What program options should be considered in modeling future missions?
- How might space construction be accomplished?
- What would a space construction base look like?
- How do the Shuttle, the Spacelab, and the Space Construction Base elements relate in a logical and evolutionary plan?
- What milestones, schedules, and costs appear reasonable?

On the following pages, the answers developed during the study for the critical questions outlined above are summarized. A more detailed discussion of the study results may be found in the Technical Volume (Final Report, Volume 2) and its associated Appendices (Final Report, Volume 3, Books 1 and 2).

## TOWARD WHAT KEY OBJECTIVES SHOULD SPACE STATION SYSTEMS BE DIRECTED DURING THE REMAINDER OF THIS CENTURY?

At the outset of Part 1 of this study, it was determined that the Outlook for Space report (NASA SP-386, January 1976), supplemented by data available through the Study of the Commonality of Space Vehicle Applications to Future National Needs (Aerospace Contract NASw-2727), provided an excellent descriptive data base of key goals and objectives. It was not the intent of the present study to justify specific space program objectives per se, but rather to identify the range and extent of potential requirements that might reasonably be imposed on a Space Station system. Therefore, the initial step was to use this material to identify 61 program objectives as potential candidates for Space Station systems support.

The most important support feature that a Space Station can offer toward the accomplishment of any future space program goal is the availability of man as an observer, decision-maker, and operator on a long-term basis. Experience on Skylab offers substantial evidence that the presence of scientists and astronauts can contribute significantly to the success of a mission and enhance the productivity of space-flight activities with respect to modification and improvisation. Accordingly, in the initial study effort, emphasis was placed upon those potential areas where manned space programs might be expected to make a significant contribution. Forty-seven of the 61 objectives from the Outlook for Space report were identified as requiring the support of man in space, either in the Shuttle sortie mode or in extended-duration facilities.

The 47 objectives derived from the Outlook for Space and the supplemental sources were evaluated in terms of their importance as determinants in deriving requirements for future Space Station system elements. Criteria used in this ranking were: Need (degree of satisfaction of basic needs); Benefits (potential for providing significant economic benefits); Space Station Applicability: Time Frame for Implementation; Cost Confidence; Technical Confidence; and the available Data Base.

With this information, the 47 objectives were collated into ten Space Station system objectives in which manned Space Station systems appeared to have the potential of contributing significant support. These ten objectives were:

- Satellite Power System
- Nuclear Energy
- Earth Services
- Space Cosmological R&D

(Construction-Related)

- Space Processing

(Space Manufacturing)

- Cluster Support System
- Depot
- Multidiscipline Science Laboratory
- Sensor Development
- Living and Working in Space

(Support Objectives)

The objectives covered a spectrum of potential applications from commercial operations to pure science: four involved space construction of large antennas and solar arrays, five provided a supporting research and development base for other objectives, one represented an early step in the development of the area of space manufacturing. Each objective was studied independently in some detail to determine the implication for future space systems and to establish design requirements. In cases where the time frames for application of the individual objectives lay beyond the period of interest for potential Space Station program options (approximately through 1995), they were not included.* As a result of this effort, eight of the ten objectives were selected for more detailed analysis prior to the development of program options.

*It was recommended that the development of spacebased nuclear energy systems be deferred on this basis. The cluster support system concept was also deferred since it also did not show promise of sufficient application in time period of interest.

The objectives selected were the following:

- Satellite Power System (SPS) – Provide a facility for the construction of test articles and permanent space test capability for evaluation of the technical and economic feasibility of SPS.
- Earth Services – Conduct research and development and construct large antennas and associated hardware required for:
  A. Domestic and international communications services
  B. Earth and atmospheric surveys
- Space Processing – Conduct R&D to determine the technical and economic feasibility of commercial inorganic processing and biological materials applications, and support, as appropriate, the initial commercial use of these processes.
- Space Cosmological Research and Development – Perform R&D on space cosmology-related components and construct a large microwave telescope.
- Multidiscipline Science Laboratory – Provide a multidiscipline laboratory to conduct space research in the basic and applied sciences.
- Sensor Development Facility – Provide a facility for the test and evaluation of optical sensors for earth sciences and cosmological phenomenon.
- Living and Working in Space – Demonstrate long-term living and working in space as related to other manned space objectives.
- Orbital Depot – Perform the necessary R&D and develop the orbital operations for an orbital transfer vehicle system.

Each of the objectives selected was studied in greater depth to define the steps that would be necessary to realize the stated objective. In each case, a set of functional requirements was derived which identified specific technology advancement needs, tests that must be conducted, and processes that must be developed.

Of these eight objectives, four in particular offer the promise of: serving important needs of man on earth; advancing US preeminence in science and technology; and ultimately generating an economic

return on investment, essential if permanent government support is to be avoided.

The four major mission activities which appear to best satisfy these criteria are: a satellite power system; the provision of earth services for resource management and communications; the processing of materials in space for commercial uses; and the furthering of scientific research for the advancement of man's knowledge.

***A Satellite Power System*** (Figure 1) would provide abundant and environmentally acceptable electrical energy and reduce US reliance on foreign sources. But to be a viable option, such a system must be technologically feasible and economically competitive with alternate energy systems. An evaluation of alternative sources indicated that only two – solar satellite power systems and nuclear fusion – will have desirable safety and environmental characteristics combined with an ultimate capability for replacing depletable fuel systems. Of these, feasible technology has been demonstrated only for the satellite power system. Additionally, successful development of SPS would allow the United States to become a leading exporter of energy, since the microwave system allows economic transmission of power to any point on earth.

A system concept and design developed by NASA JSC was examined in the study to identify the technology growth requirements, the fiscally feasible production steps, and the development tests required. It was determined that the basic concept held promise of being both technologically feasible and economically competitive. A reliable judgment on these issues, however, depends on testing in space of the ability to assemble the large structures required and the development and operation of small-scale systems. During the study, a need for microwave power transmission development tests in space was also identified. A program for a full-scale operational system must be prudently tested on a small scale first to verify Space Solar Power as a viable long-term option that the US, confronted with its long-term energy problem, needs to pursue.

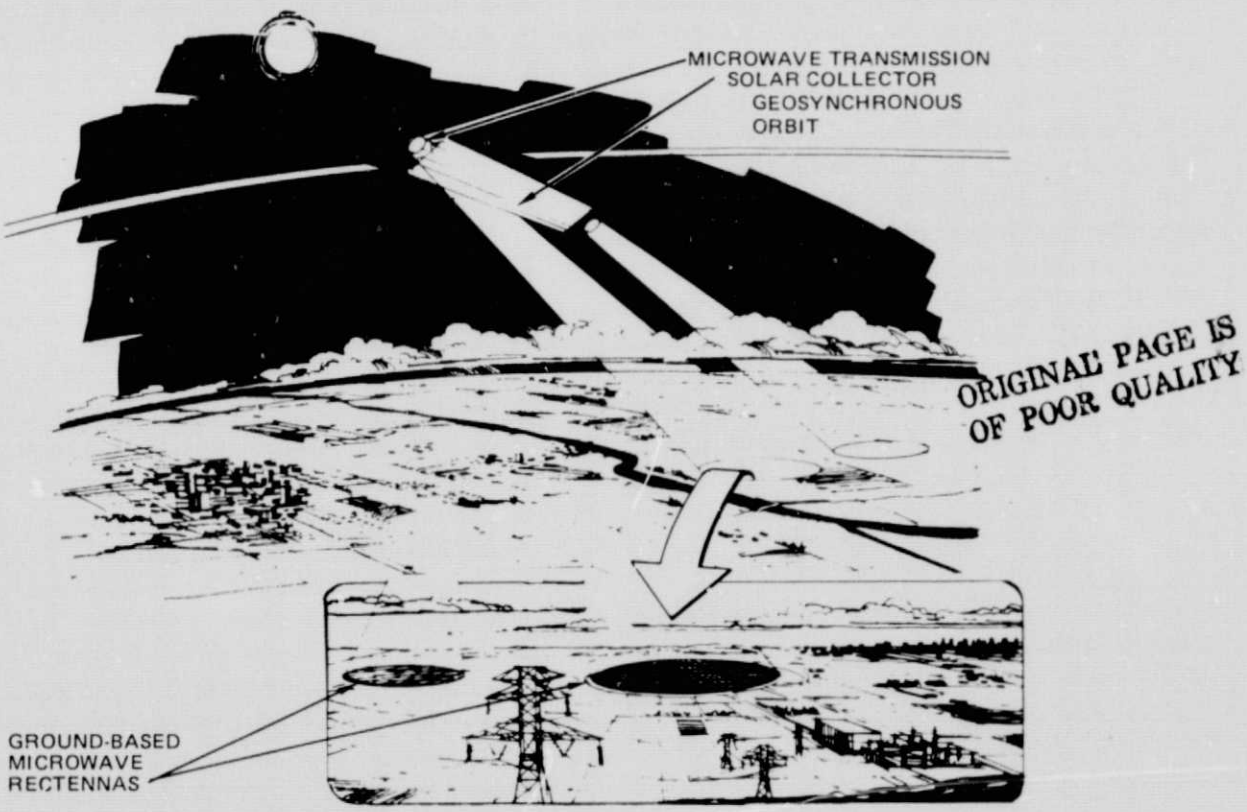


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Figure 1. Space Solar Power Concept

***Earth Services missions*** can provide greatly enhanced benefits to man on earth when utilizing the larger structures that can be assembled in orbit.

Lower transportation costs to orbit can make possible construction of large microwave antennas (radiometers), which will permit earth resources surveys of far greater scope and efficiency to enhance crop production, aid in the management of timber, fisheries, and other important resources, improve weather prediction and contribute to solution of environmental pollution problems. Such capabilities can have substantial economic benefits, estimated in the billions of dollars per year. They can also mitigate human suffering and loss of life resulting from food shortages and natural hazards whose adverse effects can be reduced by the improved earth surveys possible from space platforms.

Similarly, the burgeoning demand for communication services (Figure 2) can be met by new systems incorporating large multibeam lens antennas in orbit. Such systems would open entirely new possibilities for public communication services. They could permit direct personal contact between individuals, offer emergency communications and health services information, and provide for modernization of the postal services. In addition to the efficiencies thus made possible, such a system would not have to rely on the complex, capital-intensive ground facilities otherwise necessary if the conventional communications network had to be expanded to perform comparable functions. Development of this capability would not only allow the United States to offer a worldwide direct communications service, it would also create an enormous market for the personal transmitters/receivers.

As in the case of space solar power, these earth services activities rely on critical technologies, including the construction of large precision structures in space, which need to be developed and tested in an operational mode. High-resolution, multispectral, large-diameter radiometer antennas

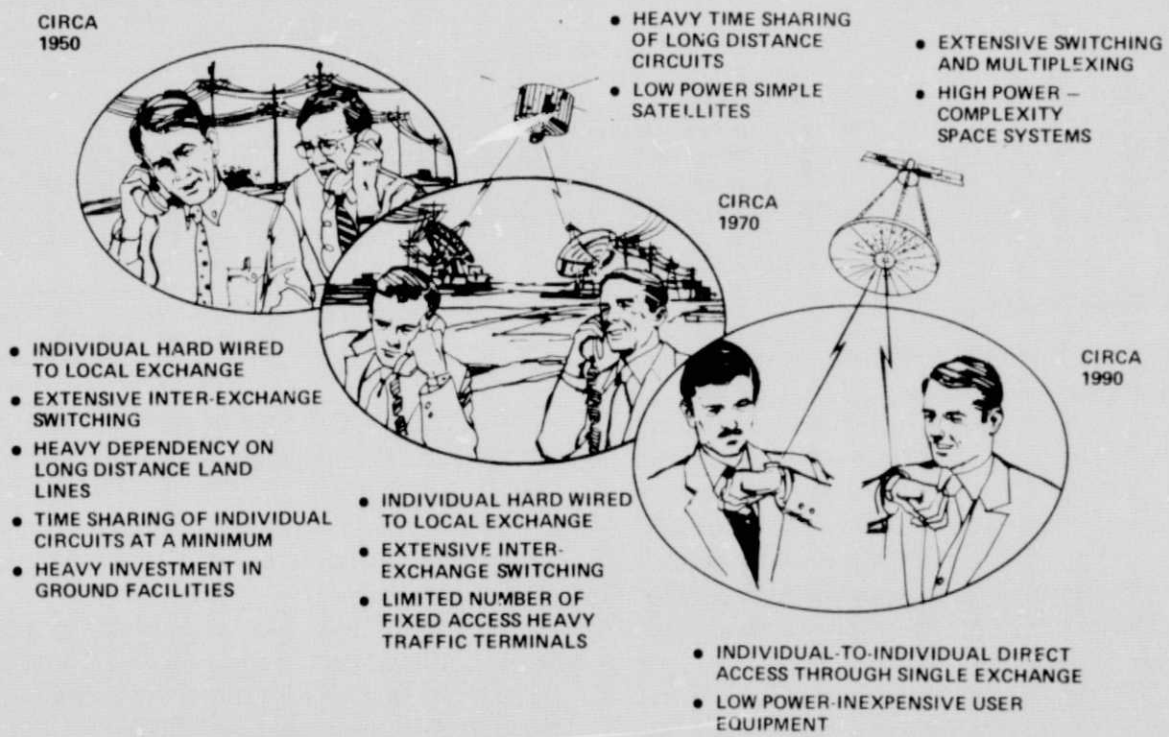


**Figure 2. Complexity Inversion for Future Personal Communications**

are needed for earth resources surveys; electronically sophisticated, large-diameter multibeam antennas in space would perform the complex switching functions needed for the expanded communications system.

***Space processing*** (Figure 3) of materials and products and their commercialization through privately sponsored ventures is a third significant activity. Certain characteristics of space make such processing attractive: the greatly reduced gravity environment, high vacuum conditions, and access to solar radiation for heat and high power levels.

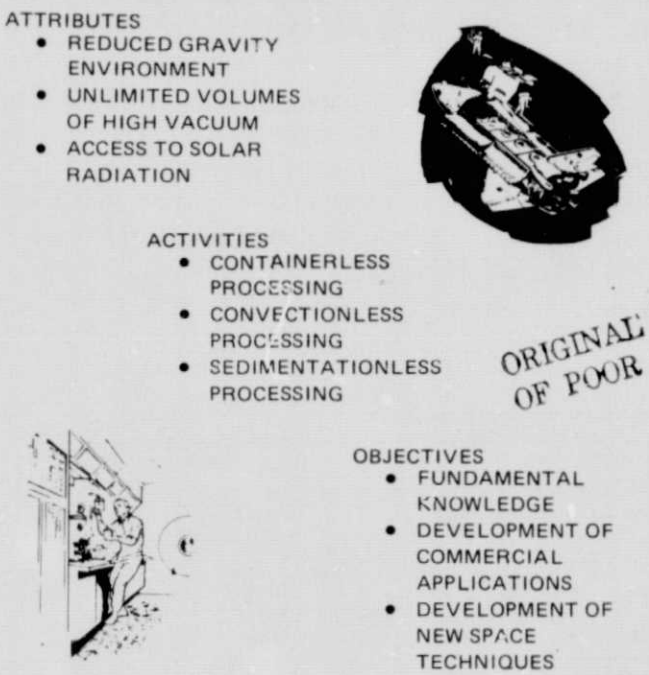


**Figure 3. Space Processing**

These conditions, singly or in combination, make possible certain processing techniques either impossible or infeasible on earth; for example, containerless and convectionless processing, and processing without the disadvantages of sedimentation. Space refining and shaping of crystals has important applications in the semiconductor industry, and electrophoretic separation of biologicals has important implications for pharmaceutical use, to cite only two examples.

There is significant interest in the commercial sector in the possibility of space processing. However, there are risks involved in commercialization of these new potentials. To attract private venture capital it will be necessary to conduct pilot plant flight demonstrations before commercial interests will be willing to assume the risks of large capital investments.

***Space science*** (Figure 4), the fourth type of activity whose benefits can be exploited by the greater use of space, meets the criteria discussed earlier, but in an indirect way. The benefits of space science to man lie in the expansion of human knowledge through astronomy, physics, and the life and earth sciences. Such efforts surely serve to advance the nation's stature in the vanguard of science. The return on investment, while not directly calculable, must be counted an essential part of later applications whose economic value can be measured (Figure 5).

Although all eight objectives were considered in establishing the functional requirements that must be satisfied by future space systems, primary emphasis in the study analysis was placed on the four key areas indicated above.

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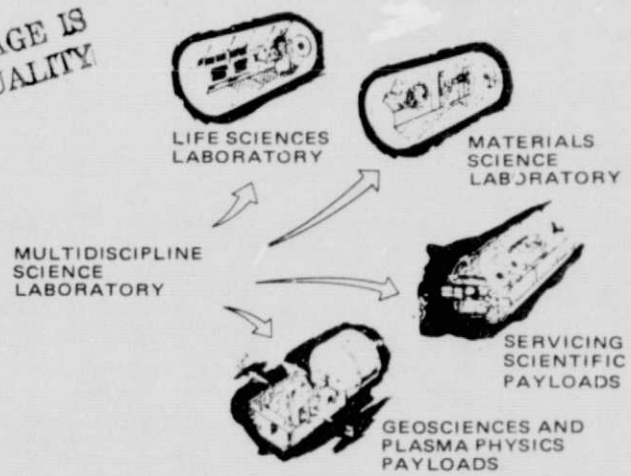


**Figure 4. Multidiscipline Support of Scientific Missions**

## WHAT REQUIREMENTS DO THE KEY OBJECTIVES PLACE ON SPACE SYSTEMS?

Once the key objectives were established, system implementation concepts were developed in order that the key technology development steps could be identified. This in turn established the specific areas in which Space Station support would be required. For each area requiring Space Station support, an objective element was defined – an objective element being the physical facility, equipment item, test apparatus, structural assembly, etc., needed to perform the required function. These

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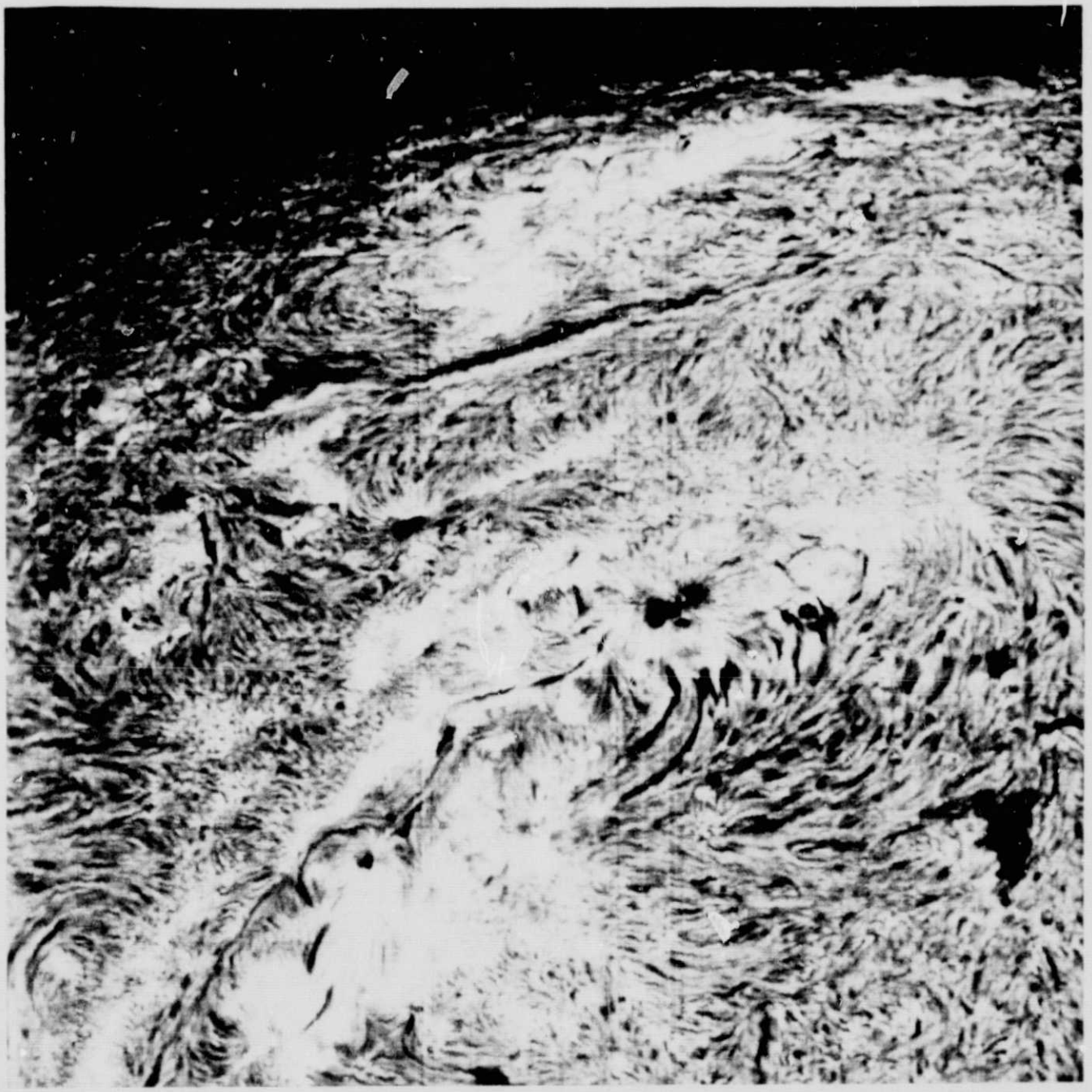

Figure 5. This is a Spectroheliogram made in the red light of hydrogen, courtesy of the Hale Observatories. The earth is profoundly affected by the sun and its changing character. Every form of life is dependent directly or indirectly for its survival on energy received from the sun. The interaction of solar energy with the atmosphere generates our weather, and the atmospheric winds in turn are the initializing forces behind all ocean currents. Learning more about the sun and understanding solar cycles and the physical properties that control them will significantly affect our lives and life styles in the future. This search for knowledge will lead to improved information on the gross physical properties of the photosphere and chromosphere (e.g., temperature, pressure, composition distributions), a better definition of the granulation characteristics, spot prominences, magnetic fields, and the temporal relations of the active phenomena of the sun. Understanding the solar energetics requires substantial angular resolution improvement, especially in the ultraviolet regions of the spectrum over that possible from earth. Because of attenuating characteristics of the earth's atmosphere, these wavelength regions can only be investigated from platforms in space.

objective elements and the requirements they impose form the basic set of information needed to define facility requirements and potential program options.

As an illustration of the factors considered in the analysis of requirements for future space facilities, three examples are presented: satellite power systems, space processing facilities, and earth services facilities.

### Satellite Power System (SPS) Objective

For a commitment to be made to SPS, demonstration of technical capability and economic feasibility is required. Answers are required to fundamental questions on the cost of fabricating large structures in space, the practicality of large-scale energy collection and microwave transmission, the control of radio frequency interference effects, and other critical issues. Then, if a commitment decision is made, a development program must be initiated.

Accordingly, a minimum system capable of resolving many critical technology issues at the lowest possible cost was derived and was designated Test Article -1 (TA-1). This would be followed by a second test article (TA-2), which would provide cost data and information pertinent to the determination of how an SPS might be fabricated and assembled on orbit, as well as key end-to-end functional verification of such issues as two-dimensional phase control and the thermostructural effects. This effort would be planned to be completed in time to provide data and experience to support programmatic decisions with respect to SPS before the Nation's energy needs become critical in the 1990's. Finally, assuming a commitment is made, a partial prototype test article (TA-3) of the full SPS would be fabricated.

Schematic descriptions of the SPS test articles, TA-1 and TA-2, that were considered in this study are presented in Figure 6.

A summary of the critical SPS test article functional requirements is listed in Figure 7 along with an indication of the capability of the various SPS

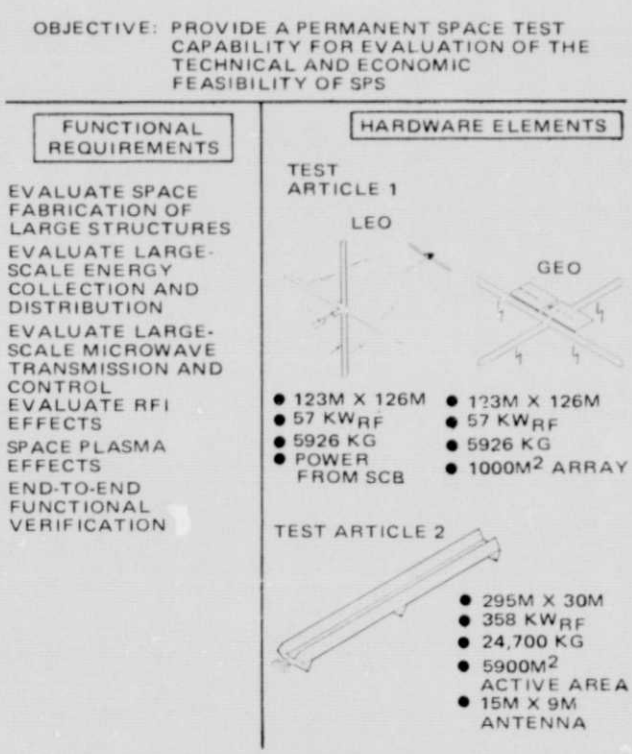


**Figure 6. Satellite Power System (SPS)**

objective elements to resolve the issues. The functional requirements are SPS technology advancement issues. This list was derived jointly by the Johnson Space Center, the Lewis Research Center, MDAC, and Raytheon. TA-1 operates in both low earth orbit — LEO (TA-1L) and geosynchronous orbit — GEO (TA-1G), while TA-2 is used only in LEO. TA-1 would be used to resolve microwave control issues, including operation in the GEO environment. TA-2 would be involved primarily with investigating the solar collector issues, full power density microwave transmission, and system end-to-end functional verification.

### Space Processing Objective

Space processing will ultimately be justified if it can become a commercial source for materials and products not obtainable at competitive costs on earth. In this context, this objective has a strictly commercial emphasis, i.e., made-in-space products having a unique utility in the economy. Therefore, the characteristics of the program to transition from

| FUNCTIONAL REQUIREMENTS | OBJECTIVE ELEMENTS | | |
|---|---|---|---|
| | LEO | | GEO |
| | TA-1L | TA-2 | TA-1G |
| EVALUATE SPACE FABRICATION OF LARGE STRUCTURES | | | |
| • SOLAR COLLECTOR | | X | |
| • MICROWAVE ANTENNA | X | X | X |
| • STRUCTURAL INTERFACES | P | X | P |
| EVALUATE LARGE-SCALE ENERGY COLLECTION AND DISTRIBUTION | | | |
| • 20K VOLTS | P | X | |
| • SWITCHING | | X | |
| EVALUATE LARGE-SCALE MICROWAVE TRANSMISSION AND CONTROL | | | |
| • IONOSPHERIC DEGRADATION OF PHASE CONTROL SYSTEM | | | X |
| • THERMOSTRUCTURAL EFFECTS ON PHASE CONTROL SYSTEM | X | X | X |
| EVALUATE RFI EFFECTS | | | |
| • DIRECT TRANSMISSION FROM AMPLITRONS | X | X | X |
| • SWITCHING AND ROTARY JOINT SOURCES | X | X | P |
| • VOLTAGE LEVEL REGULATION | P | X | P |
| • IONOSPHERE INDUCED | | | X |
| SPACE PLASMA EFFECTS | | | |
| • ARCING & LEAKAGE | X | X | X |
| • SPACECRAFT CHARGE PHENOMENA | | | X |
| END-TO-END FUNCTIONAL VERIFICATION | | | |
| • THERMOSTRUCTURAL INTERACTION | P | X | |
| • PHASE CONTROL SYSTEM | X | X | |
| • POWER TRANSFER/ ROTARY JOINT CURRENT DENSITY | P | X | |
| • PROTOTYPE MANUFACTURING/ASSEMBLY PROCESSES | P | X | |

P = PARTIAL SATISFACTION

**Figure 7. SPS Objective Element/Requirements Matrix**

R&D to full-scale commercial production in space must reflect the following:

- Continued applied R&D activities in basic chemistry and physics, materials sciences, pharmaceuticals, electronic materials applications, optical materials and components, and other man-made products that offer a commercially significant potential.
- Development of in-space processes and procedures that ensure control of material characteristics, uniformity, dimensional precision, and on-schedule production in quantities commensurate with industrial operations.
- Demonstration of production yields in sufficient quantities and quality to ensure commercial interest and economy as opposed to merely demonstrating scientific or technical feasibility.
- Demonstration of man-machine interactive designs that will take cost-effective advantage of automated, semiautomated, and manual operations, including all aspects of the production process (i.e., fabrication, assembly, test, quality control, packing, and transportation).

Three cases were selected as being representative of a broad class of future commercial space processing activities (see Figure 8). These cases were biologicals, ultrapure glasses, and shaped crystals. The first case was the production of the enzyme urokinase, which involved a process designed around a separation procedure and two cell growth cycles. This process is typical of the production of a biomaterial in final form in space. Based upon the results of the successful electrophoresis technology experiment conducted on Apollo-Soyuz, this type of process may offer great improvement in the product potency over that possible on earth. The encouraging results of the Apollo-Soyuz experiment showed that one fraction of the cells separated produced six times more urokinase activity than did ground-based control cultures. It is predicted that additional improvements in all steps of the procedure (i.e., the separation process and the two growth steps) will yield an overall projected improvement of 600 times that which could be expected on earth. This potential improvement by space processing could prove to be the breakthrough necessary to make such life-saving pharmaceuticals available to the public, thereby making possible their use in routine clinical practice rather than in experimental medicine only.

The second case selected described the production of an ultrapure glass in space, representative of the high-technology unique materials useful in new and novel products of the future. At the suggestion of Owens-Illinois, the prototype product upon which this case was focused consisted of glasses formed in space which would possess superior characteristics insofar as optical properties and internal impurities are concerned. These improvements could be important in fiber optics applications. The TRW Systems group estimates the ultrapure material used in the manufacture of fiber optics

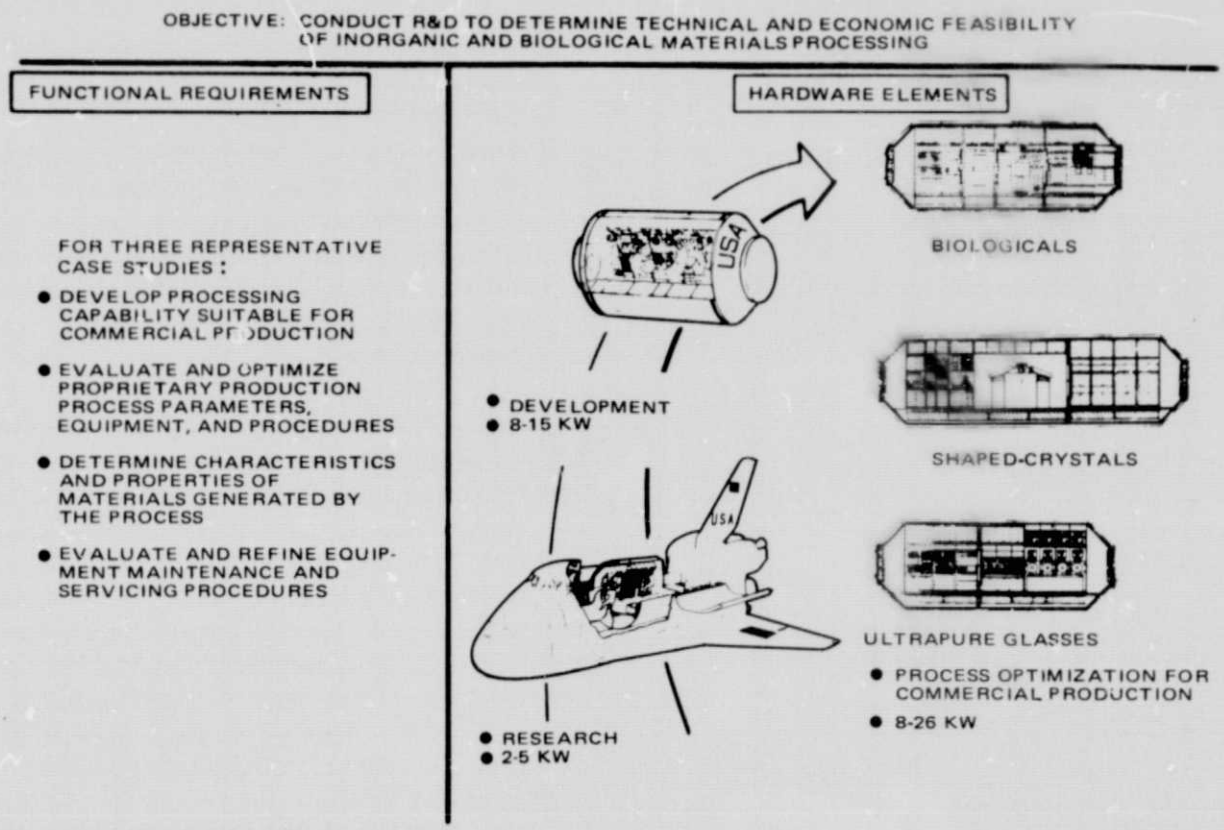


**Figure 8. Commercial Space Processing**

communication cables could reduce the transmission losses to the point where a savings in other components of the communication system (i.e., repeaters) would equate to $59,000 for every kilogram of ultrapure glass used in the system. Projected annual savings, along with the specific savings, were estimated by TRW and Owens-Illinois to be $236 million at the time the original case selection was analyzed.

The third case selected was production of semiconductor-grade silicon in ribbon form. A survey of private industry provided a projection of the demand for integrated circuits, for which semiconductor silicon is the basic raw material, to reach 200,000 kg (478,000 lb) by the year 1990. At a finished cost of $100,000 per kilogram, this demand equates to a $20 billion annual market. This high market potential represents one of the more important features of this third case.

In order to initiate the space processing demonstration project a Space Processing Development Facility is required, suitable for the evaluation of processing procedures and equipment for eventual transition to commercial production. The preliminary tests which need to be conducted in space prior to developing dedicated facilities for specific applications must be fully supported by trained personnel for durations from 30 to 90 days. While only modest crews will suffice (one to two persons), the onboard activities in the initial development facility will involve operating the processors and analyzing the product in a systematic manner. The equipment accommodated by the facility must permit evaluation of biologicals and inorganic materials. Certain materials will be contamination-sensitive; and isolation of the processing apparatus will be required. The electrical power and equivalent heat rejection requirements of the initial development facility will range from 8 to 15 kilowatts. The initial equipment installed in the facility will be derived from Spacelab-type payloads and equipment racks, such as those items that will be developed within the Space Processing Activity (SPA) program. As the testing program matures,

other equipment items with dedicated capabilities will replace the initial units, thereby necessitating an equipment changeout capability. Some level of equipment maintenance will be required to ensure the continuing availability of the facility.

**Earth Services Objective**

To conduct passive microwave radiometry, the Outlook for Space called for long-wavelength microwave system development leading to operational systems for conducting marine resource evaluation, all-weather crop prediction, and regional water balance forecasting. (Figure 9) Other studies, among them the Study of the Commonality of Space Vehicle Applications to Future National Needs, Aerospace NASW2727, have suggested the high value and use of small portable personal communication facilities, electronic mail, and other communication-oriented capabilities.

To accomplish these objectives, the designs, tools, methods, and materials required to construct, assemble, and test large antennas in space which will maintain their structural integrity and beam-pointing capability when subjected to thermal and other stresses must be developed. It is anticipated (reference Aerospace NASW2727) that three antenna types for radiometric and communications applications will require development, i.e., a parabolic dish, a multibeam lens, and large-phased array antennas. Radiometry antenna design analysis conducted during the study revealed a fourth category, a parabolic torus used in a scanning radiometer. As a precursor to the development of 300m or larger antenna systems, it appeared desirable to introduce a smaller prototype into the antenna development program at an early stage. The intent is to reduce development risk and the cost of changes or modifications incurred in the learning process of on-orbit large-scale construction.

Accordingly, based upon the design requirements and trade studies, design concepts for a multibeam lens antenna, and a 30m and a 100m parabolic-torus radiometers were evolved. The system and

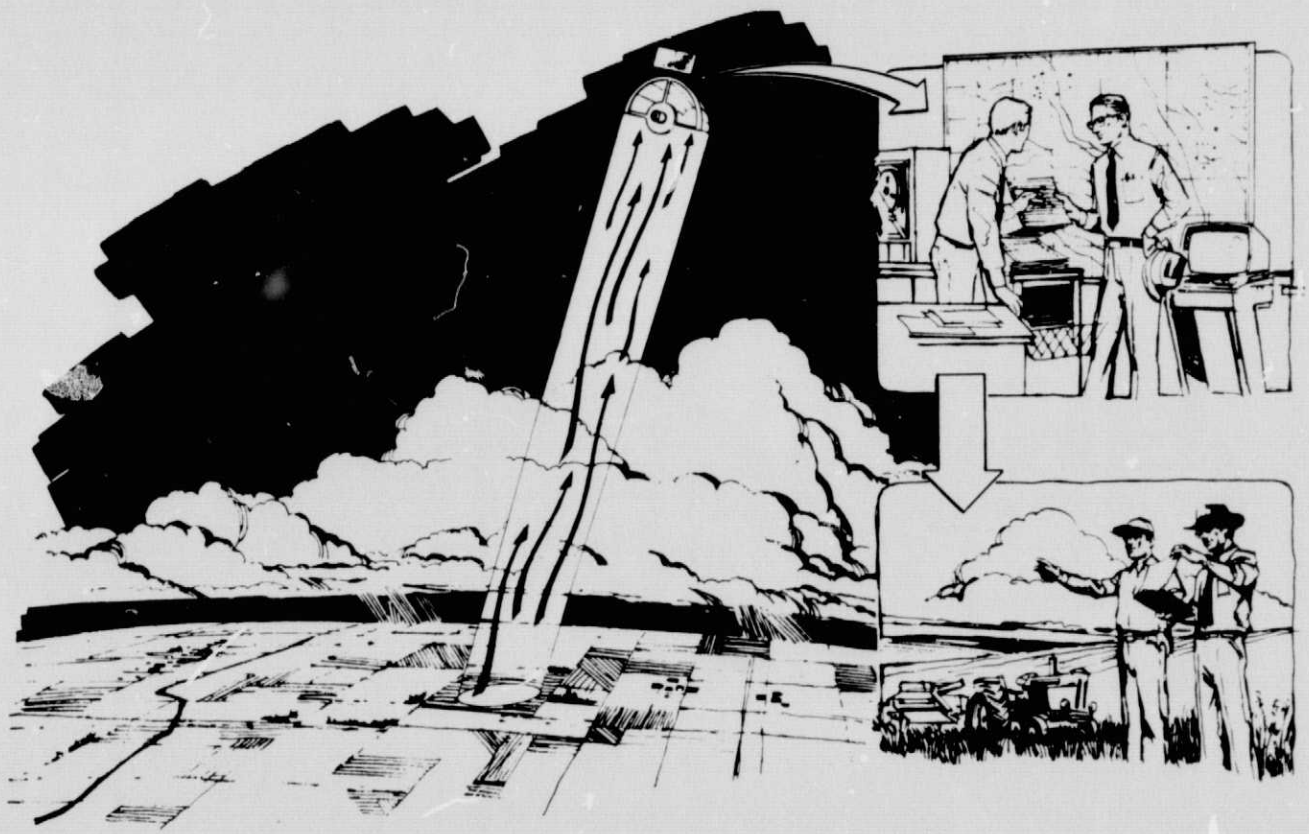

**Figure 9. All-Crop . . . All-Weather Prediction System**



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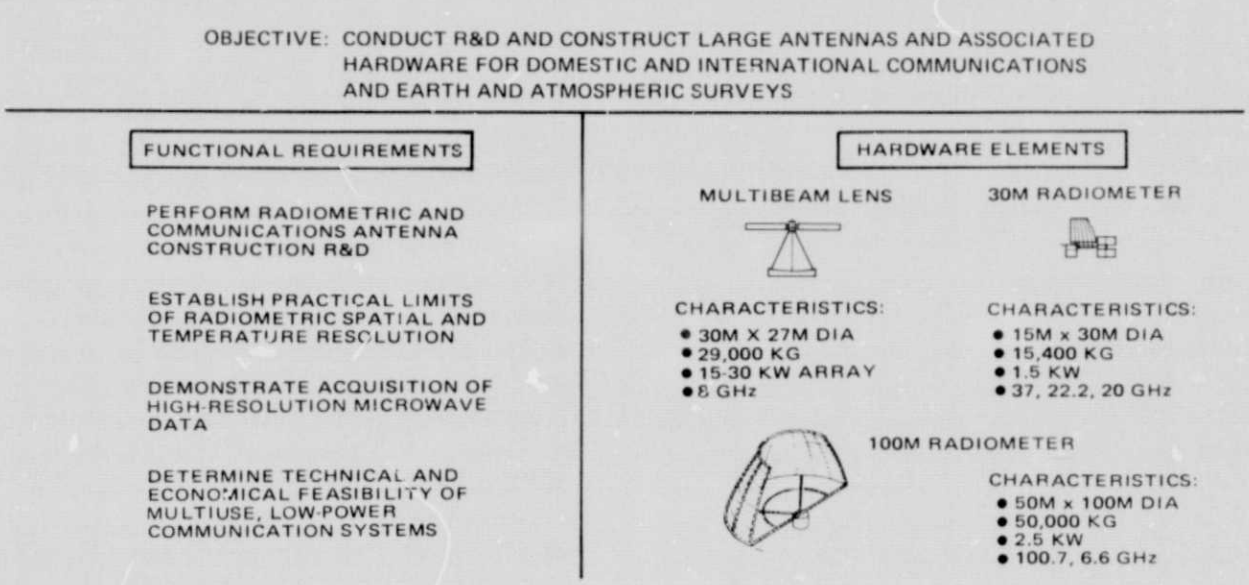



**Figure 10. Earth Services**

antenna characteristics of these antennas are summarized in Figure 10. The radiometers are designed to cover all frequency bands of interest in earth observations while scanning perpendicular to the orbit track of the Space Station. Since these satellites will be passive in nature, power requirements should not exceed 2 kW. Figure 11 gives the dimensional characteristics of the 100m parabolic torus radiometer.

Large space antennas will either be assembled in space or will be designed to be deployable. Antennas are placed in the assembly category if their shape and electronic equipment complement are such as to make deployment difficult, i.e., if unfurling mechanisms and hinges become extensively complex, and if damping must be employed to prevent excessive backlash. Another factor to be considered is the surface tolerance which can be

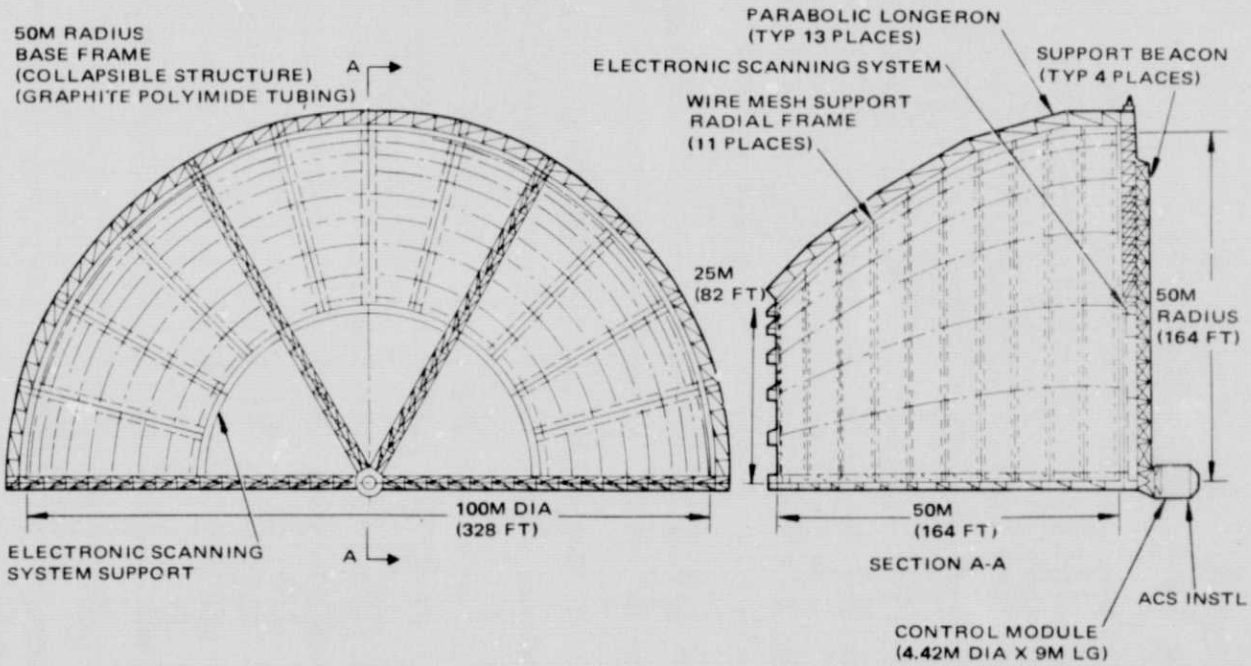



**Figure 11. 100m Parabolic Torus Radiometer – Electronically Scanned**

achieved. Higher frequencies require tighter tolerances. The multibeam lens antenna and the 30m and 100m scanning parabolic torus radiometers, which are proposed, respectively, for communications, earth observations, and limb-sounding radiometry, fall in the space assembly category due to their complex shape, tight surface tolerances, and requirement for precise alignment.

In summary, many objectives have been identified in previous studies which have the potential of satisfying a basic need or goal of mankind. Eight specific objectives have been identified in the present study which should be pursued in the near-term. Four of these objectives -- satellite power systems, earth services (large antenna systems for communications and radiometry), space science (multidiscipline science laboratory), and space processing -- represent major goal-directed program concepts. The remaining objectives, e.g., space cosmological research and development, the sensor development facility, living and working in space, and the orbital depot facility -- represent support functions that will be required as basic building blocks in the future expansion of all areas of space activity. These building blocks would not only support the four major program concepts but would provide the basic system elements capable of meeting additional requirements as they arise.

**IS THERE A COMMON POINT OF DEPARTURE IN DEVELOPING A PROGRAM PLAN WITH THE FLEXIBILITY AND GROWTH POTENTIAL TO MEET THESE OBJECTIVES?**

There are specific advantages which a space platform offers for the pursuit of any scientific or applied endeavor, namely the ability to view the celestrial sphere without the filtering effects of the earth's atmosphere, the ability to view broad regions of the earth's surface within short periods of time, and the ability to work in the different physical environment of weightlessness and high vacuum. In addition to these advantages, the availability of a crew in space for extended periods permits the assembly and construction of elements of mission hardware in orbit which would otherwise not be feasible to develop, since they would be too large for deployment from an Orbiter.

In the case of specific applications, such as Satellite Power Systems, a location in a geosynchronous orbit allows continuous energy collection unattenuated by the earth's atmosphere, as well as the advantage of concentrating the energy gathered into a single portion of the spectrum (the microwave region) where transmission losses through the atmosphere will be minimal.

In the Space Station System Analysis Study a variety of mission hardware items (Figure 12) were derived to satisfy mission requirements in the areas of Satellite Power Systems (SPS), radiometry, and multiuser communication systems. In order to provide the power level, bandwidth, frequency range, spatial coverage, etc., to satisfy the mission requirements, large items of mission hardware are needed. By way of example, Figure 13 schematically illustrates the relative size of some of the various systems elements that were determined to be necessary for the pursuit of the key objectives in the development of earth services and space-based solar energy systems, as compared to the size of the Orbiter.

Thus, the common point of departure in developing a program to meet the needs of future space missions is the basic requirement for construction facilities in orbit, including the associated support facilities. Accordingly, a major facet of the present study has been directed toward establishing the basic feasibility of space construction and in developing the most cost-effective method of constructing the objective elements required.

The analysis of construction techniques and of the various mission hardware items required has led the study team to the conclusion that space construction, though it presents a technical challenge, appears to be achievable within the current state-of-the-art and can be a cost-effective approach to satisfying future space hardware requirements.

Considerable commonality was found among the capabilities needed to accomplish the objectives examined in this study. The commonality of operational requirements can also result in a desirable

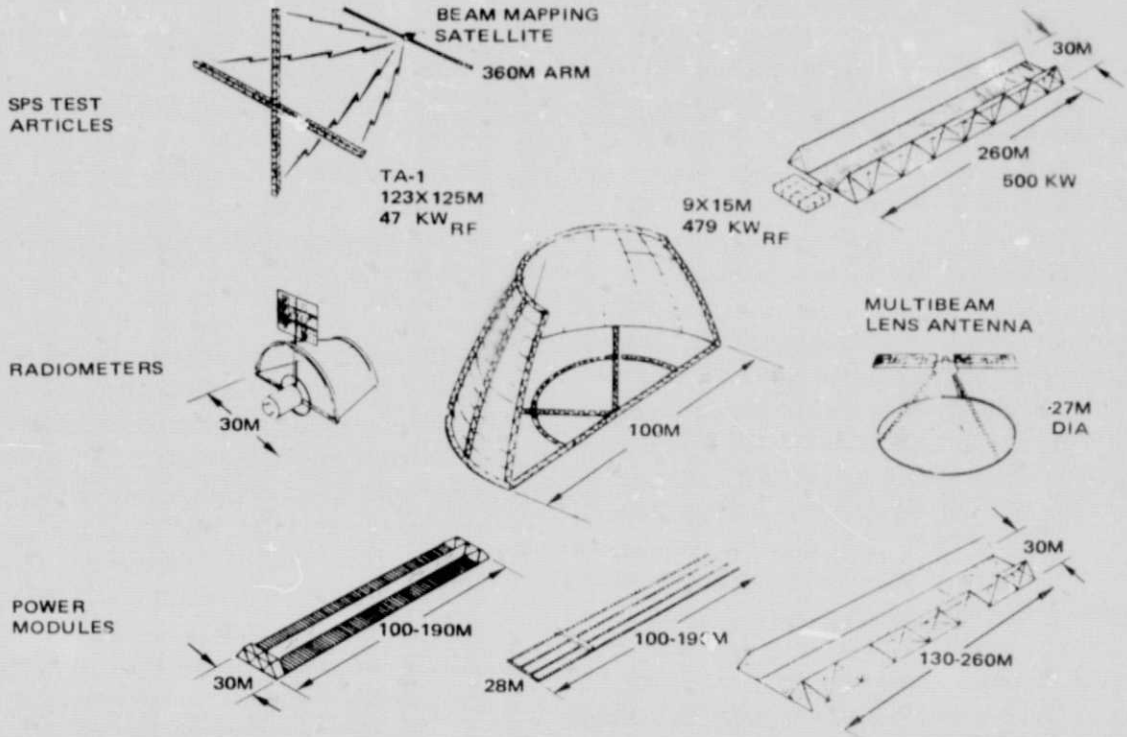



**Figure 12. Mission Hardware**

synergism in cost savings, which can be expected to extend at least over the next 10 years. The most common support requirements were found to be the need for crane operations, space fabrication facilities, space assembly capabilities, extravehicular activities, and general support for long-duration operations. In Figure 14, major requirements for a particular objective element are indicated by a large check mark, minor requirements by a small check mark.

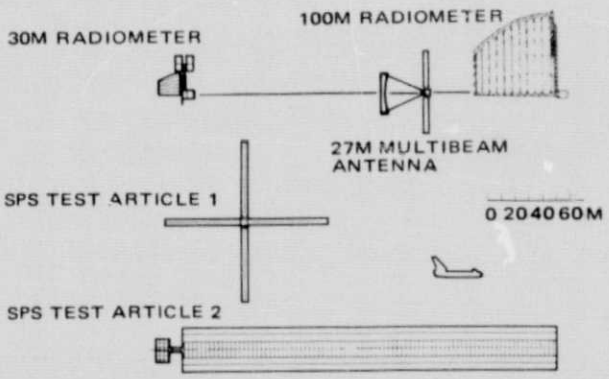



**Figure 13. Construction-Related Objective Elements**

The crane in space fulfills the same basic function as a crane on the ground. It is used to move large masses in a controlled fashion and to provide support for the various assembly functions. As can be seen in the figure, all objective elements were found to require crane operations to a major or minor extent. In particular, crane operations for SPS TA-1 and TA-2, and for the large antennas (30m radiometer, 27m multibeam lens, and 100m radiometer) are a major requirement in the fabrication and assembly of those elements. However, the laboratory-type elements basically require crane operations only initially, to position the module or to supply necessary materials.

Requirements for space fabrication facilities were identified in developing the test articles for advanced solar power satellites as well as in constructing the final operational system. Similar technology and orbital facilities will be required in the construction of large antenna systems and, to a lesser extent, space fabrication could be required in the basic buildup of the Space Construction Base (SCB) itself. Space fabrication of components, as opposed to transporting finished parts to orbit, can be economically justified if total construction costs are

CR60

| OBJECTIVE ELEMENT | CRANE OPERATIONS | SPACE FABRICATION | SPACE ASSEMBLY | EVA REQUIREMENTS | LONG DURATION |
|---|---|---|---|---|---|
| TEST ARTICLE-1 | ✓ | ✓ | ✓ | ✓ | ✓ |
| TEST ARTICLE-2 | ✓ | ✓ | ✓ | ✓ | ✓ |
| MULTIBEAM LENS ANTENNA | ✓ | ✓ | ✓ | ✓ | ✓ |
| 30-100M RADIOMETER ANTENNAS | ✓ | ✓ | ✓ | ✓ | ✓ |
| SPACE PROCESSING | ✓ | | | | ✓ |
| MULTIDISCIPLINE LABORATORY | ✓ | | | ✓ | ✓ |
| LIVING AND WORKING IN SPACE | ✓ | ✓ | ✓ | ✓ | ✓ |
| SENSOR DEVELOPMENT AND TEST | ✓ | | ✓ | ✓ | ✓ |

**Figure 14. Several Objective Elements Yield Common Requirements**

thereby reduced. In general, two conditions must be met to satisfy this requirement. First, density of the component in question must be so low that transportation costs may be significantly reduced by shipping only bulk materials to orbit. Secondly, the fabrication process "orbital overhead" costs must be less than the transportation cost saving. This second condition typically involves automation of the process to reduce required fabrication man-hours. Hence, sufficient production to amortize the necessary investment in fabrication equipment is also a strong requirement.

Based on normal ground production experience, examples of fabrication processes that may be simply automated are pultrusion (plastics and composites) and roll forming (ductile metals). Such machines are currently highly developed, and capable of producing a great variety of cross sections (tubular, channels, Z-sections, etc).

Assembly is common to all construction objectives because all mission hardware requires some assembly regardless of the construction technique used.

It is interesting to note that analysis of the operations requiring space fabrication and/or assembly revealed that significant supporting EVA effort is required. EVA was found to be much more cost effective than automation in detail assembly operations. In automated fabrication and assembly, extensive EVA was still required for tool setup. Of particular interest was the evaluation of what an EVA crewman needs to do his job. At each EVA work station, a significant complement of tools, services, restraints, force/torque reaction capability, etc., was found to be necessary. It became clear that the required equipment is beyond that which can be conveniently carried by the EVA crewman. This led to the conclusion that semicontained work stations at each EVA location are needed.*

Two EVA crewmen working together are needed not only to perform many of the tasks, but because of the desirability of having each act as the other's companion for safety.

It was found that long-duration missions were required in many areas in order for the objectives to be accomplished efficiently. In the area of long-duration crew support, basic habitability functions such as food and waste management systems, environmental control and life support systems, hygiene, etc., can be expected to be common to all of the objectives. In the same fashion, many resource functions such as electrical power systems, communications, data management command and control systems, stabilization, and guidance concepts will also have a great deal of commonality over the spectrum of potential objectives.

*This requirement was met by means of a "cherry picker" EVA work platform attached to the end effector of the crane, which permits it to be located at the various positions as required.

Establishment of an initial space facility to augment the basic Orbiter capability will allow extended-duration missions and provide in situ construction support equipment. Thus missions may be undertaken which would be impractical within brief sorties that depend totally on the Orbiter's self-contained capability. Later addition of a permanent habitability facility would allow efficient continuous operations and free the Obiter from a requirement to remain in space for long durations.

## WHAT PROGRAM OPTIONS SHOULD BE CONSIDERED IN MODELING FUTURE MISSIONS?

In investigating potential program models required to support the desired objectives, 45 candidate program options were examined. See Figure 15. These options varied as to such factors as scheduling, and the level of accomplishment as a function of orbital locations, transportation requirements, and costs. These 45 candidate programs were further refined into four generic sets or classes of program development. The first program development option (L) limited all operations to low earth orbit (400-450 km). The second program development option (LG-1) conducted most operations in low earth orbit but provided the opportunity to conduct some test operations in a geosynchronous sortie mode. The third program development option (LG-2) provided for both low earth orbital and geosynchronous orbital operations with longer term construction and test operations also being required in geosynchronous orbit. In the fourth program development option (G), all operations were scheduled for accomplishment in geosynchronous orbits.

In examining these program development options, two types of operations were considered:

- Shuttle-tended operations, during which the Orbiter provides all crew support and a major share of the SCB's operational support.
- Continuously manned operations, in which the Orbiter supplies only the launch transportation and is docked periodically to the SCB to transfer crew, cargo, and consumables.

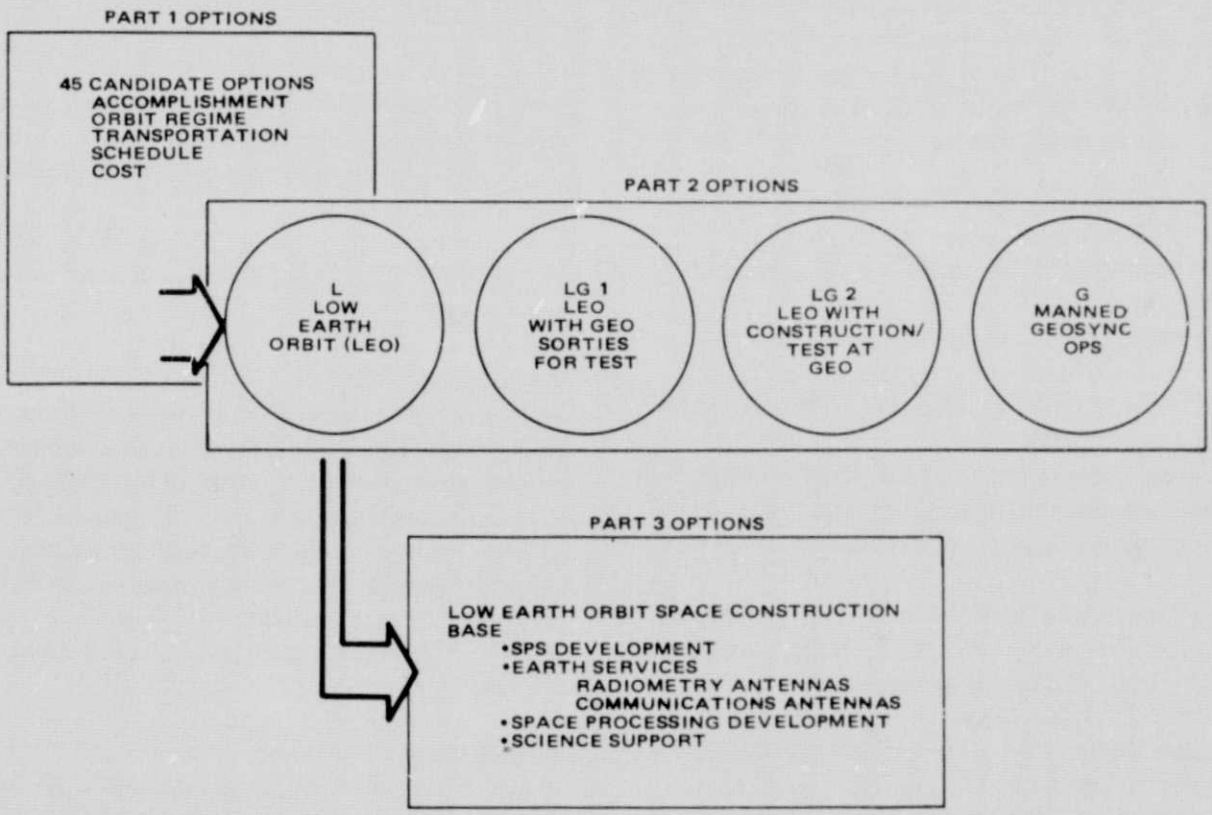



**Figure 15. Program Options**

For Program Option L, two basic cases were investigated. In one, the initial operations were Shuttle tended, evolving later into a continuously manned operation. In the second, all program activities were implemented from the beginning in a continuously manned system.

Of these two modes, the Shuttle-tended concept can provide an early space construction fabrication and assembly capability at an initially lower funding rate. Furthermore, crew requirements are compatible with the Orbiter's support capability of up to seven SCB crewmen. Of these seven, the Orbiter commander assumes the responsibility for SCB/Orbiter operations, and the remaining six would be available for shift work.

The continuously manned conceptual approach to the SCB requires provision for crew accommodations in addition to the power and construction facilities required by the Shuttle-tended configuration. In this operational mode, the crew would be continuously available, with rotation taking place on 90- to 180-day periods.

Program Option LG-1 (Figure 16) expanded the LEO activities to include construction of large structures in LEO, which were then transported to GEO for test and operations. These activities would use a continuously manned SCB in LEO and an Orbital Transfer Vehicle (OTV) for transport to GEO; manned test and operations in GEO are accomplished by GEO sortie missions or by use of a small Space Station at GEO. As indicated on the figure, all objective element activities were undertaken wholly or in part at LEO, and only those gaining significant advantage from GEO were proposed to be transferred to that location.

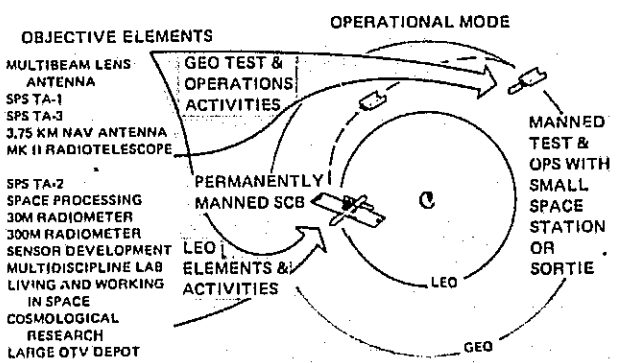



**Figure 16. Program Option LG1**

Program Option LG-2 expanded on LG-1 by providing for the construction at GEO of those objective elements to be used there. This was proposed to be accomplished by providing a continuously manned SCB at GEO in addition to the one at LEO. Logistics would be supported by Shuttle and an OTV.

For Program Option G, all activities were confined to GEO. Two operational modes were also investigated for the GEO case:

- Early Shuttle-OTV sortie mission support of objectives at GEO, supplanted by a full, continuously manned SCB at a later time.
- Construction and activation of a full, continuously manned SCB in GEO prior to any operations at GEO.

Although G is a viable option, this operational mode suffers from relatively higher transportation costs than the LG Program Options.

In the synthesizing of program options, the objective elements (which are items of flight hardware) were grouped into the various potential program options that could be accomplished in the orbital operational regimes at LEO, GEO, and combinations thereof.

Each program option was defined as a complete program, including the space construction base hardware, mission hardware, and all required transportation system elements. This approach permitted direct comparison of accomplishment versus cost for various program options.

The conclusion reached during Part 2 of the study was that the preferred approach to program planning would be to keep all initial construction activity at LEO, with only completed assemblies being transported to GEO. For comparable programs, this approach would result in a transportation cost savings of at least $2.6 billion dollars. Other factors, such as the greater radiation hazard for the

crew at GEO and the requirement for Shuttle growth, further substantiated the desirability of keeping construction programs in LEO. By keeping all early activities in LEO, a program with the lowest initial investment is realized, since the development of orbital transfer vehicles can be deferred until a much later time period. Once this conclusion was reached, the study emphasis was directed toward analyzing the low earth orbit operations in greater detail to provide the basis for modeling future missions. It is recognized that it may be determined that production of SPS is most economic when undertaken in GEO. If so, development of a GEO operational capability becomes a prime objective, and this program direction should be modified. However, at this time most opinion seems to favor LEO assembly of SPS, although this conclusion must be labeled tentative.

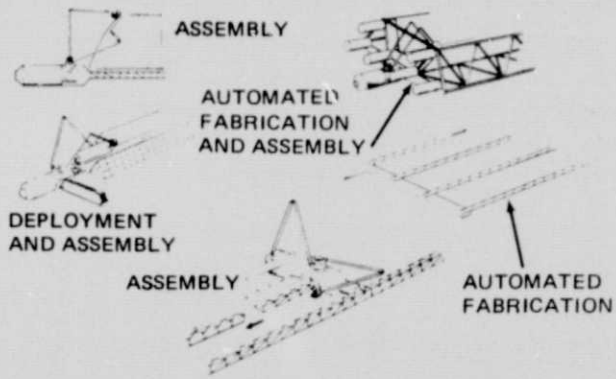



**Figure 17. Construction Using the Fixed Work Station Concept**

## HOW MIGHT SPACE CONSTRUCTION BE ACCOMPLISHED?

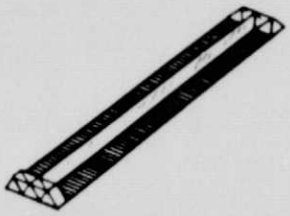
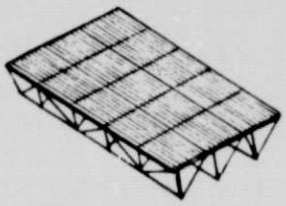
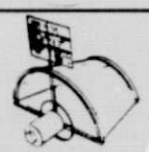
To establish the feasibility of a space construction system, the study team investigated two basically different approaches to space construction. The first approach is characterized by a fixed work station, where the parts are moved to the work station. This type of system is similar to production assembly line operations in factories where the material flows and the process machinery remains stationary.

The second approach to construction system design is characterized by a traveling work station which is transported to the work. In this case, ground analogs are found in construction of ships and buildings where the site of the construction is a fixed geographical location and cannot be moved.

The study has concluded that in space, moving the work to the work station is the most efficient approach and results in a lower-weight, less costly work station and substantial reduction in total effort. This conclusion is valid even for very large structures since, in zero gravity, the equipment and power required to hold, translate, and rotate the work is minimal. Using the fixed work station, (see Figure 17) the part is either (1) assembled on a standoff which has a turntable which rotates the part past the work station as construction proceeds, or (2) is "extruded" by having the part fabricated and/or assembled at the close-in work area, and as each section is finished, it is pushed out and a new section constructed. This is done either continuously or in steps.

One or more techniques for constructing each item of mission hardware, as noted in Figure 18, were developed in the study. Analysis of the attendant construction process then permitted the writing of a common set of requirements on the Space Construction System. As an example of the process followed, the analysis for the first test article (TA-1) in a solar power satellite system development program will be described.

TA-1 consists of two long orthogonal beams – one 123m long and one 126m long, and, for the case illustrated in Figure 19, would be assembled in orbit using components fabricated on the ground. The arms are made up from truss beams approximately 15m long which are delivered in a collapsed configuration stored on a pallet. The pallet support structure has a double section which unfolds, resulting in the pallet being over twice as long as the individual stored 15m beam segments. The first collapsed beam segment is removed from the pallet and transferred to the other side, where it is deployed and electronics installed. This erected 15m section is then moved to the outer portion of the unfolded pallet. The second beam section is then removed from the pallet and transferred to the other side,

| | SIZE | TYPE | NO. OF CONCEPTS* |
|---|---|---|---|
|  SOLAR COLLECTORS | 38 KW | DEPLOY AND ASSEMBLE | 1 |
| | 150 - 500 KW | DEPLOY ONLY<br>DEPLOY AND ASSEMBLE<br>ASSEMBLE ONLY<br>AUTOMATIC FABRICATION AND ASSEMBLY | 1<br>3<br>1<br>2 |
| | 1720 KW | AUTOMATIC ASSEMBLY | 1 |
| | 17,100 KW | AUTOMATIC ASSEMBLY | 1 |
|  MPTS ANTENNAS | 80M LINEAR | FABRICATION AND ASSEMBLE | 2 |
| | 120M CROSS (TA-1) | DEPLOY AND ASSEMBLE<br>ASSEMBLE ONLY<br>AUTOMATIC FABRICATION AND ASSEMBLY | 1<br>1<br>1 |
| | 9M x 15M ARRAY (TA-2) | DEPLOY AND ASSEMBLE<br>ASSEMBLE ONLY<br>AUTOMATIC FABRICATION AND ASSEMBLY | 1<br>1<br>1 |
| MULTIBEAM LENS ANTENNA | 27M | FABRICATION AND ASSEMBLE<br>ASSEMBLE ONLY | 1<br>1 |
| RADIOMETER  | 30M | ASSEMBLE ONLY | 1 |
| | 100M | ASSEMBLE ONLY | 1 |
| | | | 22 |

*INCLUDING LAY S, WEIGHT ESTIMATE AND CONSTRUCTION PROCESS CONCEPT LAYOUTS/FLOWS

**Figure 18. Construction Study Spectrum – Mission Hardware**

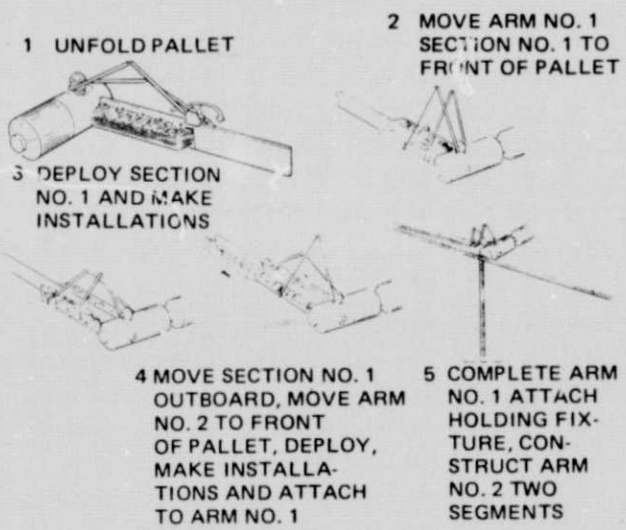



**Figure 19. TA-1 Deployment**

where the preceding segment was originally deployed. This second segment is deployed, electronics installed, and then joined to the first segment, and the combined segments maneuvered outward until the second segment rests on the unfolded section of the pallet. The third segment is then removed and the process keeps repeating until the arms of the antenna have been completed. As each arm is completed, it is installed on a separate standoff.

In the study of TA-1 construction, sensitivity analyses of the various tasks were performed to identify areas where more detailed analyses were warranted. As illustrated in Figure 20, the time required to deploy and assemble a given beam segment was determined to the nearest minute (and in some cases, second).

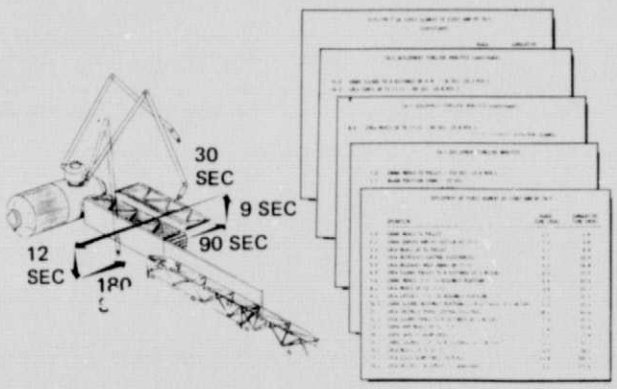



**Figure 20. Beam Assembly Transfer**

Some of the more time-consuming tasks identified for TA-1 (as estimated) were electronics assembly and mechanical alignment. Clearly these areas are ones where future analyses should concentrate.

As a result of the construction analysis, the time-line of TA-1 construction was developed. (A summary time-line based on two three-man crews, working 6-hour shifts is shown in Figure 21.) The actual construction only takes a little over two weeks followed by a two-week checkout. This results in about a one-month period from launch of the TA-1 pallet to completion of initial checkout. It should be pointed out that this is a success-oriented schedule, based on minimal time estimates, with no contingency time for rework or repair.

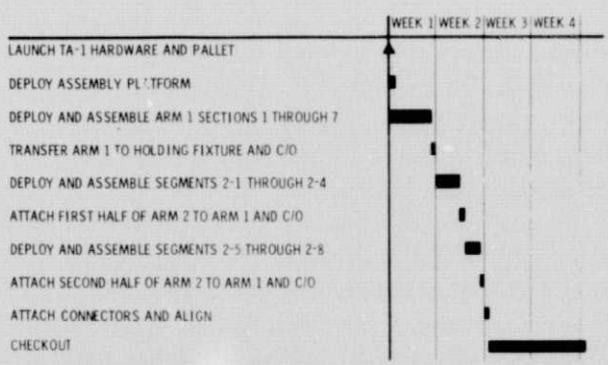



**Figure 21. TA-1 Deployment Schedule**

Using the methodology as discussed above for TA-1, operational flows and timelines for all the various mission hardware items were developed and the times required for construction of the various elements established as noted in Table 1. As can be seen in Table 1, the construction time spans, when contingency and checkout times are added, are in the general range of one to six months. These times do not include time for conducting subsequent manned tests (e.g., for TA-1, experiment operations require an additional 270 days).

Analysis of the events associated with construction of each item of mission hardware enabled the identification of requirements for construction equipment and special tools and fixtures, as summarized in Table 2. In keeping with the fixed work station construction concept, key items of construction equipment are a "cherry picker" crew work platform and a crane. The cherry picker platform supports two EVA crewmen during construction and is mounted on the end of one arm of the crane. Crane controls are located on the platform and thus the EVA crewmen can maneuver themselves about the work station. The other arm of the crane is used to transfer and position parts and assemblies. A strongback having a telescoping capability and a turntable which can maneuver the mission hardware item under construction to the work station also is utilized. Considerations of the relative positioning capabilities resulted in a requirement that the crane have a reach of 35 meters, and the strongback be capable of being extended up to 52 meters. Also required are several items of tooling peculiar to mission hardware, and a Space Construction Module, which can provide production test control computation, a shop for repair of parts and tools, berthing ports for material pallets, test control consoles, etc. This total set of equipment is illustrated in Figure 22.

To provide a more detailed set of requirements (than those shown in Table 2) for design considerations, additional effort was placed on selected topics. As an example, the possible functions that a crane could perform were identified and considered in developing the requirements for the crane system in terms of force, reach, degrees of freedom, operational modes, etc. In general, the crane has been conceived to be a very utilitarian device capable of supporting a broad spectrum of manned activities on orbit.

**Table 1. Construction Operations Times**

| Item | Construction Time (Days)* | Contingency (Days)* | Checkout (Days)** | Total Calendar (Days) |
|---|---|---|---|---|
| TA-1 Deploy/Assembly | 14 | 9 | 15 | 38 |
| TA-1 Fab With Auto Assembly | 38 | 21 | 15 | 74 |
| TA-2 Deploy/Assembly | 19 | 12 | 30 | 61 |
| TA-2 Fab With Auto Assembly | 40 | 24 | 30 | 94 |
| Multibeam Lens Antenna Assembly | 42 | 26 | 24 | 92 |
| 30M Radiometer Assembly | 37 | 23 | 18 | 78 |
| 100M Radiometer Assembly | 104 | 66 | 18 | 188 |
| Power Platform Deployment | 10 | 6 | 10 | 26 |
| Power Platform Assembly | 12 | 8 | 10 | 30 |
| Power Platform Fabrication | 18 | 11 | 30 | 59 |
| Power Platform Fab With Auto Assembly | 20 | 10 | 30 | 60 |

*Assumes 2-Shift, 6-Day Workweek
**Assumes 3-Shift, 6-Day Workweek

A number of possible crane operations during assembly were evaluated. It was found that primary use of the crane should be to support the cherry picker platform, to maneuver/position parts, and possibly to deploy parts. Utilization of the crane for high precision tasks such as inserting pins or positioning an automatic fastening tool imposes extreme positioning accuracy requirements which may be very costly to satisfy, and thus such operations are probably not suitable for the crane.

In using the crane to maneuver and position parts the number of degrees of freedom needed were evaluated. First, to maneuver a part to a given location a minimum of three degrees of freedom are required (forward and back, up and down, and side motion). See Figure 23. Using an articulated arm crane with shoulder pitch and yaw and elbow pitch provides the necessary three degrees of freedom. However, with only three degrees of freedom, there is only one possible combination of shoulder yaw and pitch and elbow pitch angles associated with reaching a given point in space (this also holds for other three-degrees-of-freedom crane configurations involving degrees of freedom provided by such things as tracks and telescoping arms). As a result, there will be only one possible spatial orientation of the crane to reach that point. If there is an obstacle, then the crane cannot reach the desired position unless a fourth degree of freedom is added; for the articulated arm crane, this is best provided by a roll degree of freedom in the upper arm. With this, there are multiple arm orientations possible to reach a given point.

For final positioning, three additional degrees of freedom (pitch, yaw, and roll) are needed at the end effector, resulting in a minimum of seven degrees of freedom required for the crane.

**Table 2. Construction System Requirements**

| Construction Item | Shuttle Hardware Delivery Launches | EVA | Cherry Picker Platform | Crane (Reach-m) | Turn-Table | Standoff (Length-m) | Auxiliary Work Area | Special Tools |
|---|---|---|---|---|---|---|---|---|
| TA-1 Deploy/Assemble | 1 | X | X | 30 | X | 30 | X | |
| TA-1 Fabrication Automatic Assembly | 2 | X | X | 20 | X | | | Tube/Truss Assembly |
| TA-2 Deploy/Assembly | 3 | X | X | 25 | | 17 | | |
| TA-2 Fabrication Automatic Assembly | 5 | X | X | 35 | | | | Tube/Truss Cap Maker Auto Beam Assembly |
| MBL Assembly | 3 | X | X | 30 | X | 15 | | |
| 30m Radiometer Assembly | 1 | X | X | 25 | X | 17 | | |
| 100m Radiometer Assembly | 6 | X | X | 30 | X | 52 (Telescoping) | X | |
| 250-kW Power Platform Deployment | 3 | X | X | 25 | | 17 | | |
| 250-kW Power Platform Assembly | 1 | X | X | 20 | | 24 (Telescoping) | | |
| 250-kW Platform Fabrication | 1 | X | X | 30 | | | | Composite Beam Maker (1m) |
| 250-kW Platform Fabrication Automatic Assembly | 3 | X | X | 35 | | | | Cap Maker Auto Beam Assembly |

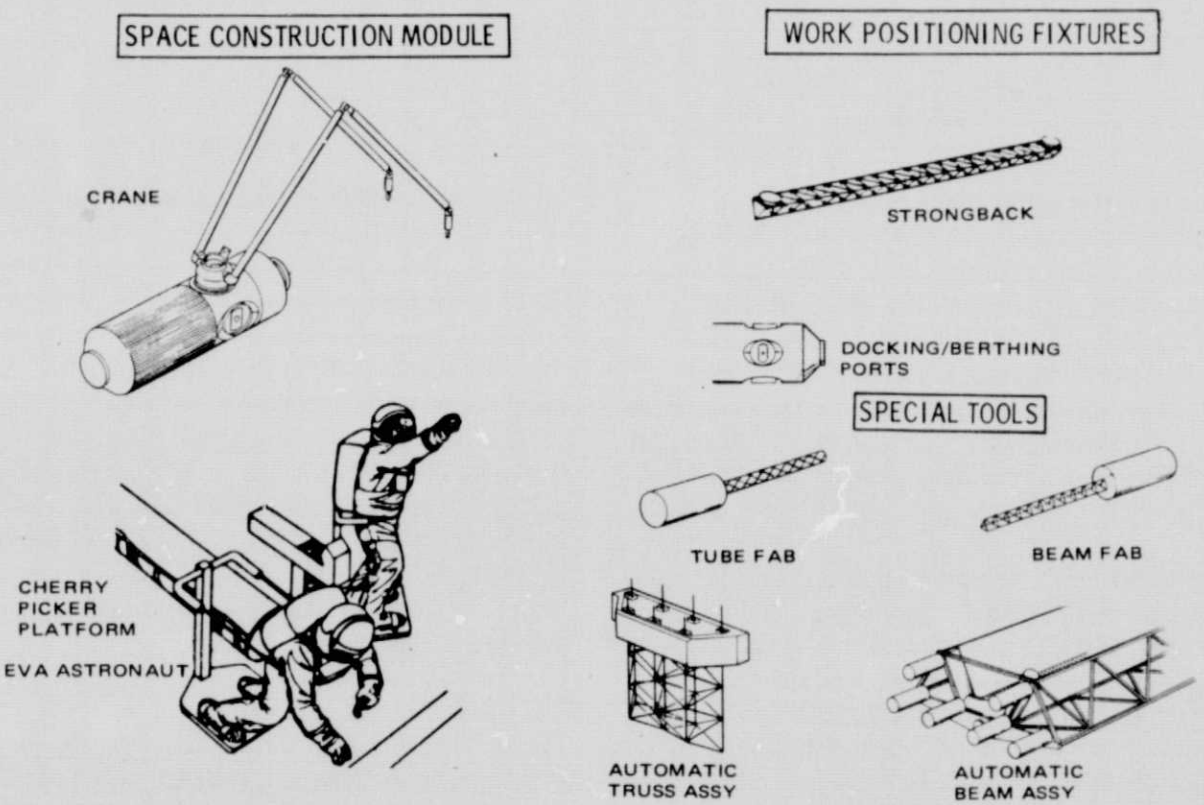



**Figure 22. Fixed Work Station Construction System**

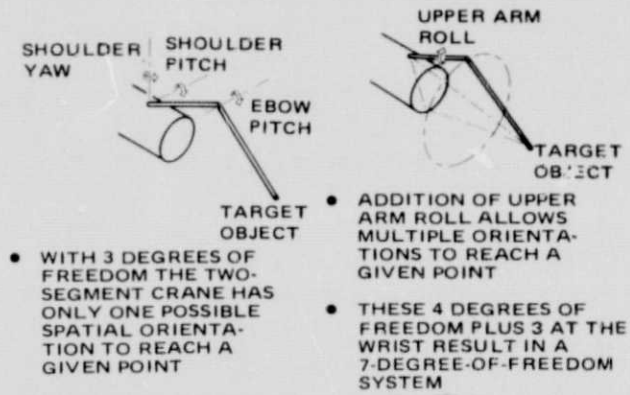



**Figure 23. Arm Access Around an Obstacle**

Having developed the geometry requirements for the crane, it was then necessary to establish basic performance requirements. One key requirement is crane translation rate. For very heavy items, such as an SCB module, translation rates can be (and probably should be) relatively slow. However, in construction activities, the crane should be able to maneuver parts and the cherry picker more quickly. In order to establish a desirable rate, sensitivity analyses of crane translation rates were performed (Figure 24) considering the various mission hardware construction jobs. The results of the analysis revealed that average translation rates of 0.25 to 0.5 m/sec are desirable. Slower rates tend to have a significant impact on construction time; faster rates do not materially decrease construction time, but could influence the crane development costs significantly.

The current results of design and performance analysis of the crane illustrated by the foregoing are summarized as follows:

- Manipulate assemblies and berth modules up to 45,000 kg (100,000 lb).
- 35-meter reach and general grasping capability.
- Degrees of freedom:
  - Wrist joint (pitch, yaw, roll)
  - Shoulder joint (pitch, yaw, roll)
  - Elbow joint (pitch)
- Arm tip force capability of 220 N.
- 0.5m/sec max rate with no load.
- Arms operated independently.
- Auxiliary control from cherry picker platform.
- Vernier positioning mode using external force (astronaut) at tip.

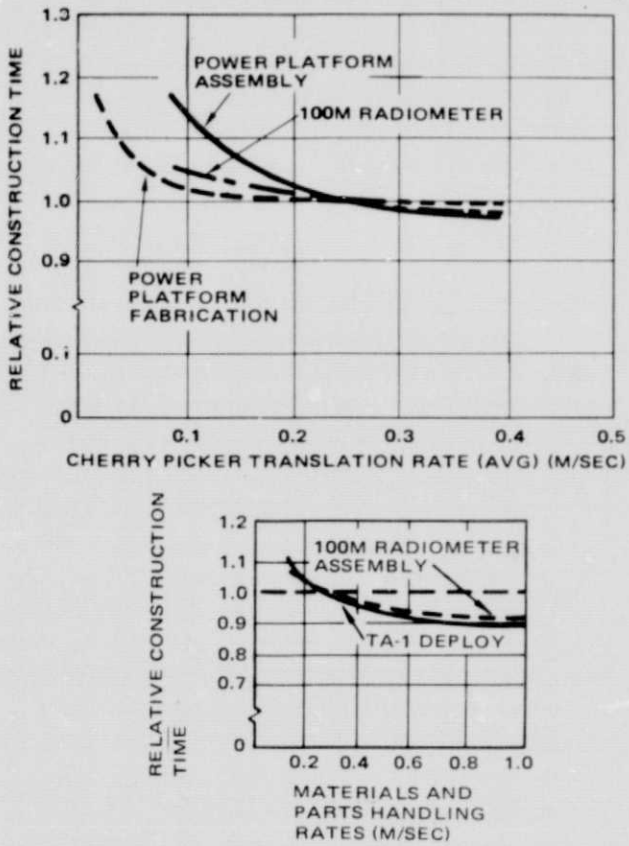



**Figure 24. Crane Translation Rate Sensitivity (Normalized)**

- Unobstructed view of the assembly area for crane operator.
- Collision avoidance software and/or max torque override.
- Automatic joint lock in case of joint motor failure.
- Damping provided by an arm lateral velocity feedback system.

The crane is used both to maneuver parts/assemblies and to berth modules. The necessary reach for each of two arms is 35m and an average rate capability of 0.25 to 0.5 m/s is required for construction tasks which require manipulating items up to about 1,500 kg in weight. The system also needs software for collision avoidance and a rate feedback system for damping.

Another area receiving additional emphasis was the analysis of the requirements for EVA. A significant amount of EVA is required in all space construction activities. Use of EVA is cost effective in non-production detail assembly tasks (as opposed to automated or remotely controlled equipment).

Even in automated construction, significant EVA time is required for tool setup. It should be noted that the total US EVA experience approximates only 50 manhours, most of which was accumulated in the Skylab missions. Mission hardware items defined in this study range between 300 to 800 EVA manhours each.

Because of the importance of EVA to space construction, the study has examined the physiological effects of the solar radiation environment on EVA operations. Analyses were conducted for EVA crewmen, considering an integrated dose for various EVA career times. Earlier results indicated that an EVA crewman using a currently planned shuttle suit could work only a very short period (a few days at most) before exceeding an allowable dose. In an attempt to solve this problem (other than through use of more restrictive suits utilizing denser shielding material), timelining of the specific EVA demand was performed. It was found that by scheduling two EVA shifts a day back-to-back, and avoiding the South Atlantic anomaly, crewmen could work for extended careers without encountering significant radiation dose problems with currently planned suits. (See Figure 25.)

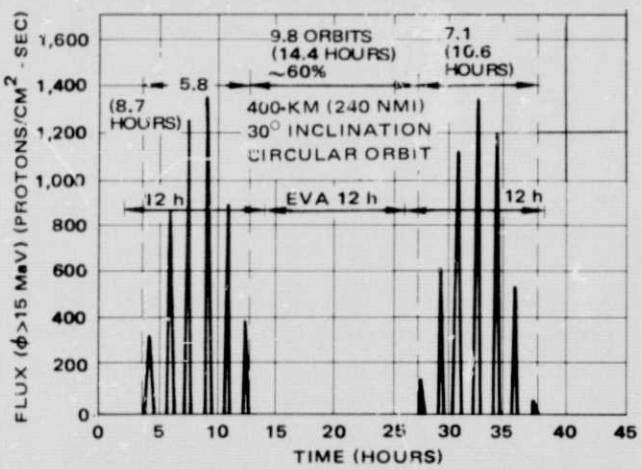



**Figure 25. Proton Flux Versus Time During Several South Atlantic Anomaly Passes**

Based upon the EVA analyses, it would appear that with careful planning of activities, the radiation environment does not present any critical operational problems at low orbital inclinations. For higher inclinations, such factors as stay time, scheduling of activities, and solar activity assume critical proportions. While these problems are no insurmountable, their existence would favor SCB operations at the lower inclinations.

During the analysis of possible construction techniques for the various mission hardware items, several conclusions were reached by the study team. First of all, it was concluded that construction of the structures considered in the study can be accomplished within the current state-of-the-art. This statement is not intended to imply that significant developments aren't needed, because some are. However, it does mean that no new technological breakthroughs are apparently required. As an example, feasible methods of constructing large structures on-orbit have been identified. What has not been resolved is the most cost-effective way of accomplishing the attendant activities of alignment, repair, checkout, inspection, calibration, subsystem installation, etc. The conclusion of the study is that these are probably best performed by EVA workmen. This approach tends to minimize the early costs as compared to those which would result from automating a broad range of detail tasks.

Automation, however, can provide cost savings in certain areas. The results of the study indicate that for limited quantities and/or precision structures, prefabrication on the ground with on-orbit deployment/assembly is the best approach. As the structures become very large, or exhibit requirements for repetitive tasks, on-orbit fabrication and automated assembly can become cost-effective.

Another important conclusion of the study of construction techniques is that a very simple system can satisfy the construction requirements. A crane, a work-positioning fixture, the capability to support EVA activities, and a facility to provide shop, data handling, test control, etc., functions when coupled with mission-hardware-peculiar tooling are all that are needed. Further, although the resulting construction system has been designed to satisfy the requirements of a specific set of mission hardware, it exhibits potential for being useful in other missions. Figure 26 provides an indication of how the system developed in the study could be used to construct a very large system.

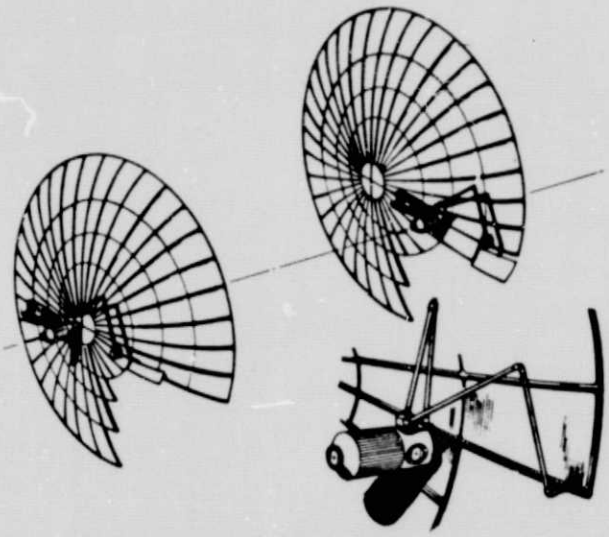


**Figure 26. Construction of Large Structure**

## WHAT WOULD A SPACE CONSTRUCTION BASE LOOK LIKE?

The three essential parts of the complete space station concept are the transportation system, the mission hardware, and the space construction base itself. The basic transportation requirements in the foreseeable future will be provided by the Space Transportation System. Mission Hardware will depend upon the specific programmatic objectives selected by NASA. The space construction base, however, will be a universal space mission support facility. As such, the underlying principle in the selection and definition of the space construction base was to ensure system flexibility to support a wide variety of program objectives. This design approach is necessary to provide the program planner with the fundamental equipment to establish specific programs in direct response to programmatic resources, objectives, and constraints.

The primary functional requirements of the space construction base will be to provide (1) power, (2) space construction facilities, and (3) habitability and subsystem support for the crew and the operations. For the Shuttle-tended mode, the third set of requirements will be supplied by the Shuttle. For the continuously manned mode of operation, the third set of requirements is provided by a single module, which is referred to as the "construction shack" because of the austere approach taken in its conceptual design. The power module is required to support early SCB operations. It also will augment the Orbiter's fuel cell output for selected sortie Spacelab missions or to replace the Orbiter's power system for extended missions beyond the Orbiter's current capability. Based upon an examination of the power required for the initial space construction activities and for various combinations of objective elements, see Figure 27, a long-term program having a variety of possible combinations of activities can be supported by a power module having a minimum average power output of 25 kW. Increasing this to 38 kW allows support of multiple objectives in the early phases. Accordingly, the power module was sized at 38 kW.

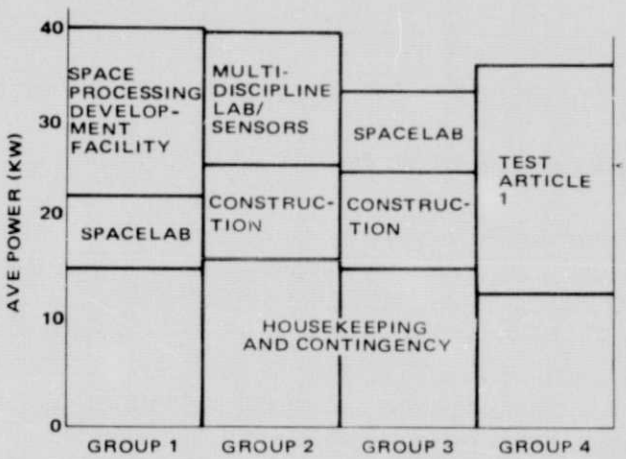



**Figure 27. Initial Power Module Sizing Considerations**

The space construction module satisfies the previously discussed construction requirements by providing facilities such as a crane to handle materials used in construction activities as well as other supporting equipment. As noted previously, the "construction shack" is a module that can replace the Orbiter in providing habitability support for the crew for extended-duration activities.

For the further development of space operations, greater power requirements will be needed than are provided by the initial power module. A larger power platform will be required as an essential growth step in the continuously manned system supporting the more sophisticated test and development programs. A power level of 250 kW peak, for example, would be required to satisfy the requirements of the TA-2 antenna system tests. Figure 28 indicates the maximum array power required to

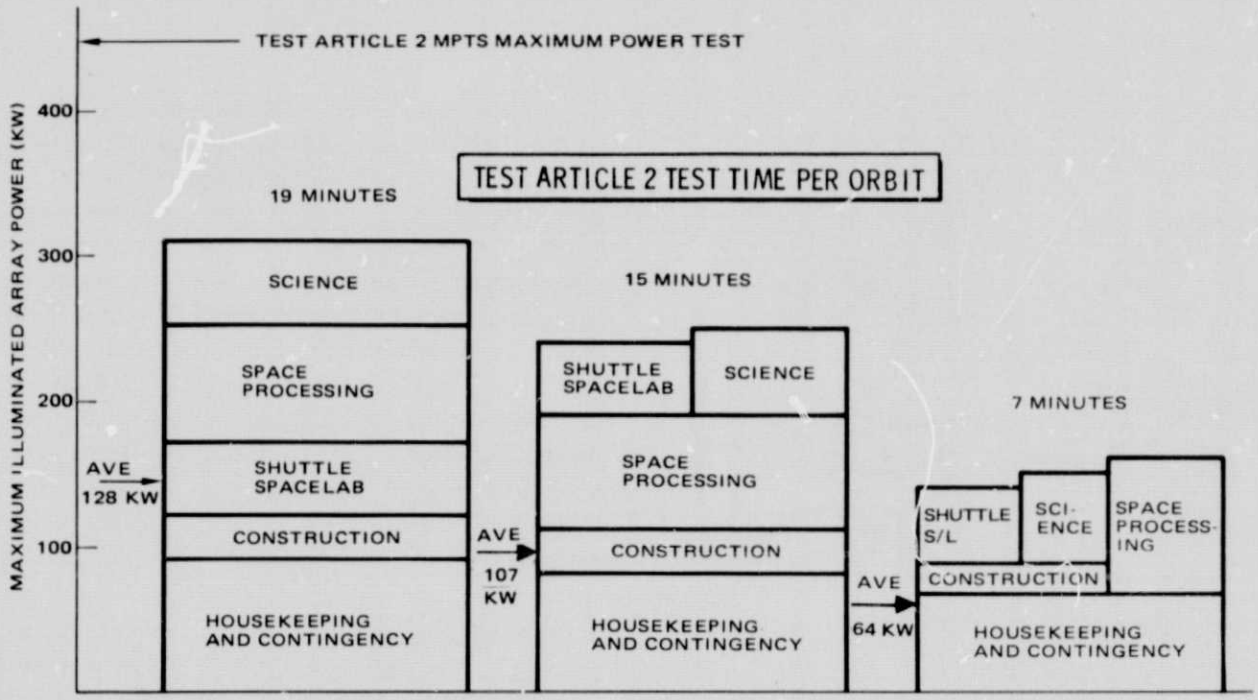



**Figure 28. Large Power Platform Size Considerations**

support various combinations of objective elements in addition to providing limited-duration testing of TA-2. It can be seen that a power level of 250 kW peak (approximately 107 kW average) would provide reasonable SPS test time at full power (15 minutes per orbit) or it would support various combinations of other activities as illustrated.

A power level of 150 kW peak or 64 kW average will support a number of activities, as shown in Figure 28, but this level would only allow about 7 minutes of continuous testing of the TA-2 antenna at the maximum power output.

Two typical orbital operational modes for the SCB were evaluated in the study in some depth: (1) Shuttle-tended, in which the Orbiter provides all crew support and (2) continuously manned, in which the Orbiter supplies only the launch transportation and is docked periodically to the SCB for several days to transfer crew, cargo, and consumables.

For the Shuttle-tended SCB concept the initial step in the buildup will consist of transporting the power module to orbit and deploying the solar arrays and radiator systems, then, the space construction module will be attached to the power module, as shown in Figure 29. As noted previously, the power module will supply approximately 38 kW at the bus location. Also, the configuration is optimally oriented with regard to the sun-solar array aspects as well as minimum drag considerations. The orientation is adequate for both low- and high-beta angle situations. This concept is further illustrated in Figure 30, in which the Shuttle-tended mode is shown supporting construction of the TA-1 antenna system.

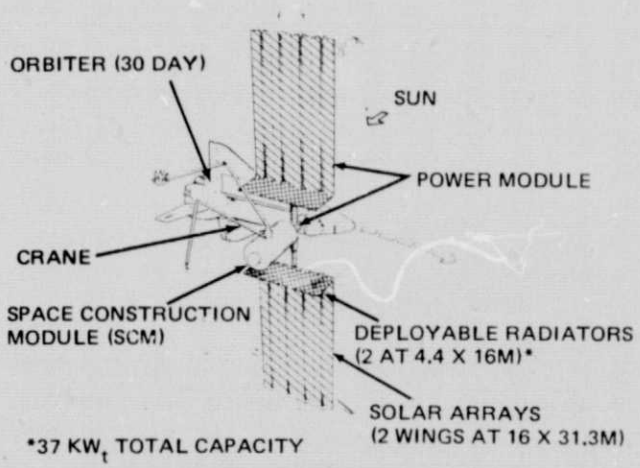



**Figure 29. Shuttle-Tended SCB Concept**

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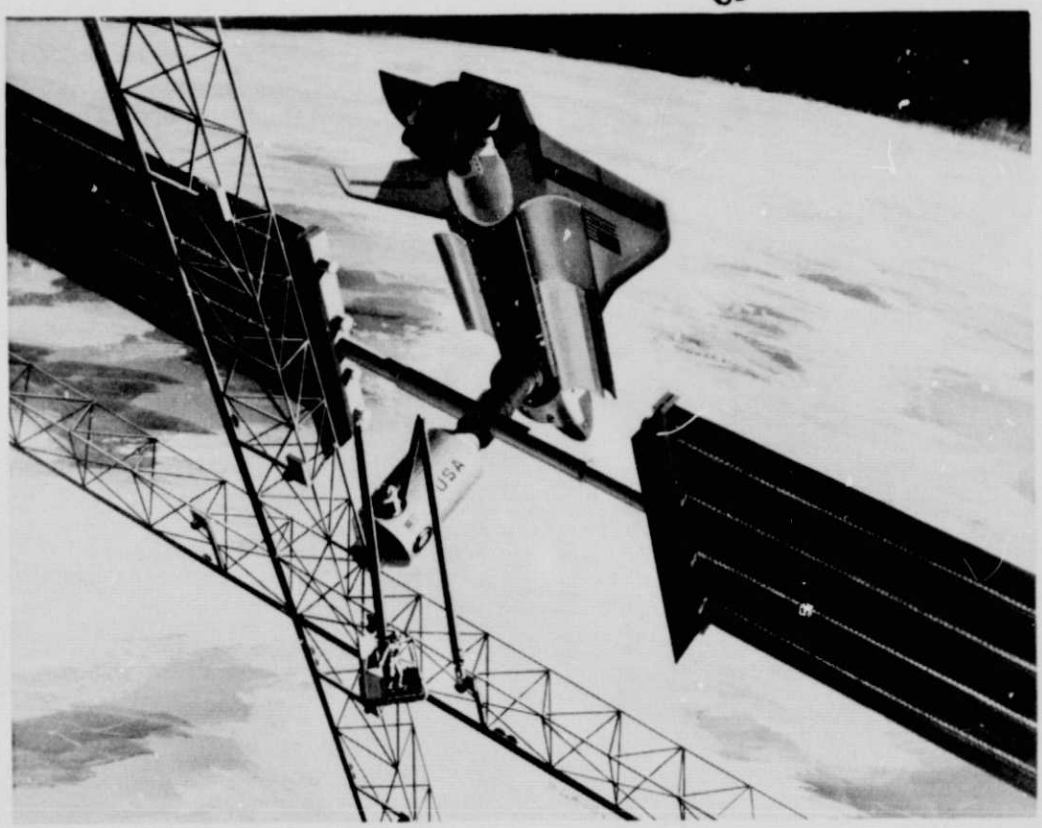

**Figure 30. Assembly of TA-1 Antenna System**

For the continuously manned mode of operations, a "construction shack" is delivered into orbit. With this addition of the "construction shack," the space construction base would have the capability of being continuously manned. As shown in Figure 31, construction of the 30m torus radiometer could be undertaken and, with the construction of the 250-kW power platform, the TA-2 antenna could be completed, followed by its testing and subsequent return to earth.

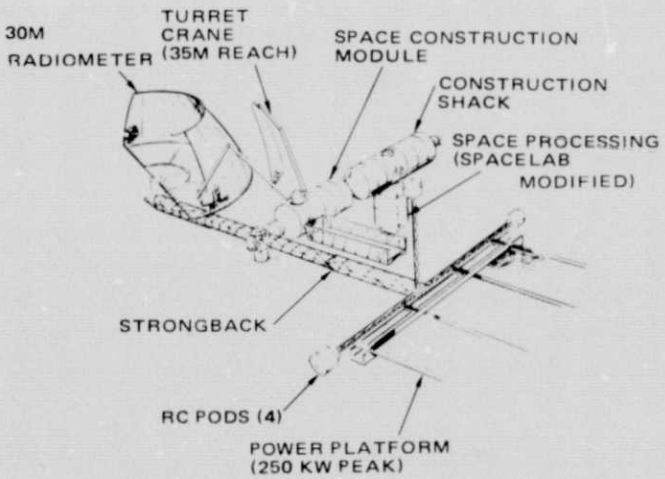


**Figure 31. SCB – Construction Base Concept Continuously Manned**

Spacelabs can be brought up and berthed to the "construction shack" at opportune times. Hence the continuously manned construction base can replace the Orbiter as the support vehicle and, since orbital duration is unlimited, greatly increase the Spacelab mission capability. Thus, continued utilization of the existing Spacelab hardware and operational program structure is ensured.

The internal layout of the space construction module concept is illustrated in Figure 32. The module arrangement is dominated by the crane turret and berthing ports. Facilities for construction/test support while adequate are not extensive.

Facilities for construction control and crew support systems (not shown) occupy the opposite side of the module. These include display and control modules, the microfilm retrieval unit, printer,

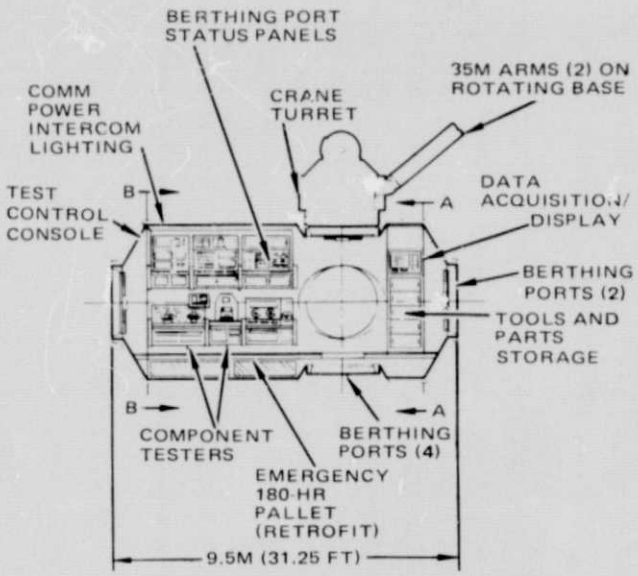


**Figure 32. Space Construction Module Concept**

schedule status panel and battery charging/gas replenishment equipment for the Orbiter suit maintenance and the life support systems. There is also a floodlight system which has been sized to illuminate a 1,000m$^2$ surface area with an intensity of 216 lumens/m$^2$ during the approximately 36 minutes of darkness per orbit. These units will require 5 kW during operation. For completeness, the berthing/docking port lighting, work position lighting tracking lights, and safety lights have also been evaluated.

The module, as presented, is not a stand-alone concept. As described earlier, it requires either the Orbiter or the construction shack and either the power module or power platform to provide subsystems and resources for its operation. As such, it serves as an adjunct to the major SCB elements with the sole purpose of supporting construction. This approach results in a low-cost system while providing the necessary flexibility to support other program options.

Continuous manning will eventually be required to permit long periods of uninterrupted work, as in the space processing area, and to reduce the cost per manhour in orbit by reducing transportation costs through longer staytimes. This requires more habitability services for the crew than can be provided by the Orbiter alone.

The "construction shack" module (Figure 33) represents an austere low-cost approach for crew quarters and facilities without compromising crew safety or performance. As shown, the module contains a two-man Orbiter airlock with an EVA hatch, a control compartment, a wardroom and exercise area in the region of the berthing ports, and crew sleeping quarters. Storage racks provide space for 60 to 90 days of consumables for a seven-man crew. The module has two pressurizable compartments separated by a common bulkhead.

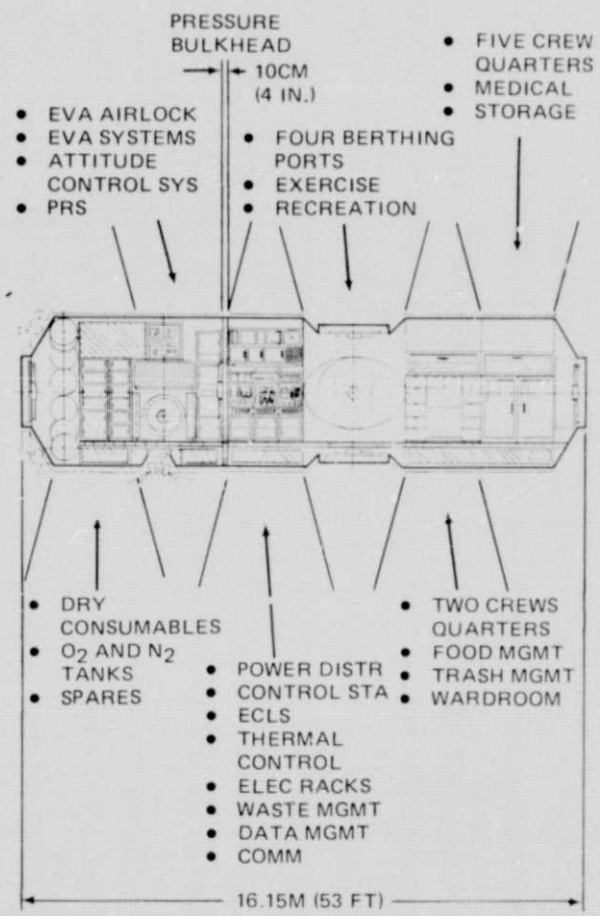


**Figure 33. Construction Shack Concept**

The functional elements of the construction shack have been divided into crew systems, EVA systems, SCB control systems, and SCB passive systems. Since the construction shack acts as an Orbiter surrogate (with expanded on-orbit duration capability), all conventional subsystems are represented.

In the iterative process of determining desirable external configurations for the SCB, all key

external system and subsystem requirements were delineated and their impact on design was assessed.

Principal factors considered were:

Orbit Keeping and Station Orientation

- Power Platform Solar Orientation
- Guidance/Navigation Sensor Location
- Drag Makeup Approach
- RCS Locations

Orbital Interfaces

- Orbiter Docking Locations – Normal and Emergency
- Orbiter Flight Corridor/Envelope
- Docking/Berthing Mechanism

Space Construction Base

- Module Handling – Buildup Sequence
- Space Construction Clearance Envelope
- Crane/RMS Reach Envelopes
- Radiator Locations
- Visibility Considerations
- EVA Movement Corridors – Normal and Rescue Procedures
- Objective Element Test Pointing Requirements

For each of the design considerations listed above, the operational requirements associated with the item were detailed, its physical characteristics noted, and design considerations outlined. From this information candidate external configurations were prepared and an iterative modification and selection process was then instituted.

An example of one of the critical design areas investigated in the study is the potentially wide variance in CG locations and moments of inertia resulting from the many potential orbiting configurations. Figure 34 represents the CG in-plane components for typical groupings of configurations using the reaction control propulsion systems for attitude control moments. One group represents the CG before the construction shack is installed, and the other represents the CG after the construction shack is installed. The connected points represent the locations of the CG for an assumed order of configuration buildups. They are, in fact, unconnected relative to time. Each point represents a completed configuration starting from the first data point in the group. The 100m radiometer is shown as a typical objective element.

The CG's are shown both with Orbiter and without Orbiter attached. The conditions with the Orbiter attached have an additional out-of-plane component

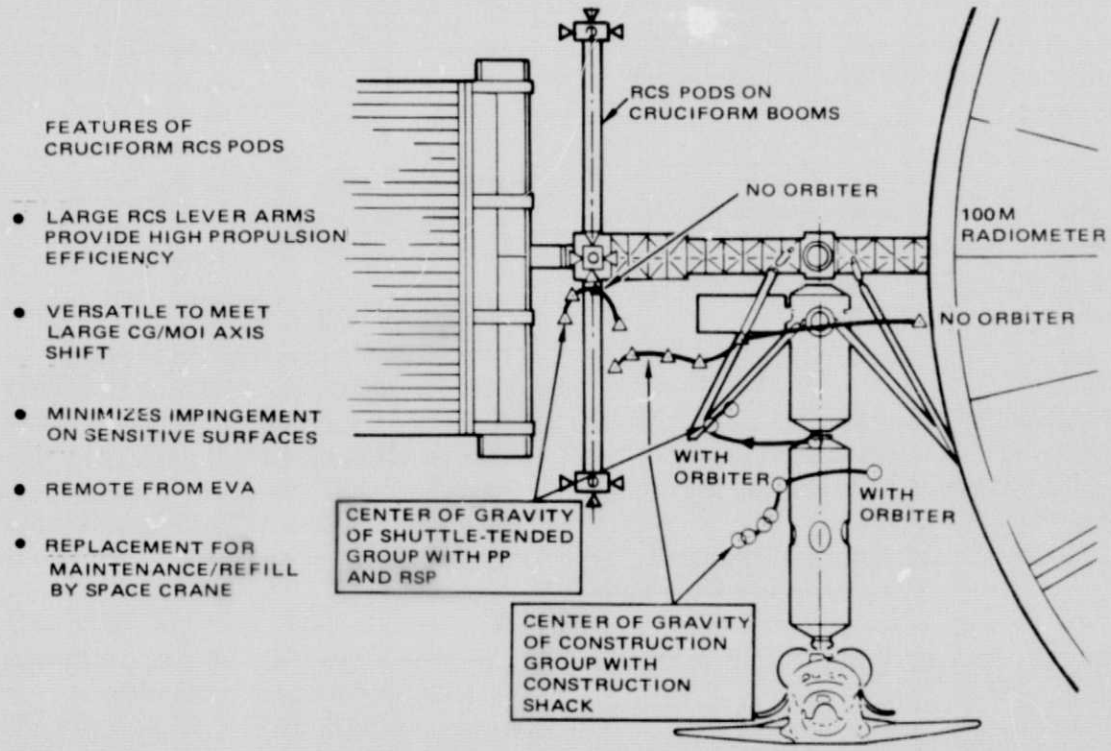


**Figure 34. SCB Center-of-Gravity Shift Versus Operational Mode**

that varies from 6 to 12m. The presence of the Orbiter also can result in a moment-of-inertia principal axis rotation as high as 33 degrees from the geometrical axes.

As shown, the CG with Orbiter attached is close to the Space Construction Module (SCM). If an RCS is included on the SCM, its small average lever arm combined with cross-axis coupling, will result in expenditure of at least three times more propellant than would be required if the RCS could be mounted at a greater distance from the CG. Accordingly, a recommended system would be to mount RCS pods on cruciform booms, as shown in Figure 34. This system also provides minimum propellant for the non-Orbiter cases in which the construction of heavier objective elements brings the CG close to (and even across) the SCM.

The remoteness of the RCS pods from the construction area (where most EVA should occur) and from the SCM and the CS will minimize impingement and contamination effects. Further, adequate redundancy in control is available with four pods in case of a thruster (or pod) failure or if it is necessary to restrict thruster firings through the software.

The pods will be accessible to the space crane for replacement with new units for ground maintenance and/or refill.

A summary of the basic design questions which were addressed during the study, and the recommendations of the study team in response to these questions are as follows:

- What should basic crew size be?
  Answer: Two three-man work crews and one man for SCB operations control – seven men total.
- Does passage through radiation belts limit EVA?
  Answer: Two 6-hr back-to-back EVA shifts can be scheduled around South Atlantic anomaly, allowing Shuttle suit in its present design to be used.
- What degree of articulation and precision of movement is required by the crane?
  Answer: 7 degrees of freedom, average maximum translation of 0.25 to 0.5 m/sec, reach of 35m, and capability for manipulation of 45,000 kg (100,000 lb) mass at rates limited by crane safety.
- What are the configuration design impacts of large CG shifts during buildup?
  Answer: Place RCS pods on cruciform booms.
- What are the configuration design impacts of high-data-rate communications?
  Answer: Boom-mounted antennas are required to eliminate shadowing.
- Are new technological developments required in subsystem design?
  Answer: Not initially. Furthermore, DDT&E costs can be significantly reduced by utilizing STS subsystem hardware.

In defining the supporting subsystems required by the Space Construction Base, it was desired insofar as possible to avoid new development programs and the associated DDT&E costs. Accordingly, the initial step in developing subsystem specifications was to examine the suitability of currently available subsystems and technology.

It was determined that a significant amount of Orbiter hardware can be used in SCB subsystems, although some modifications may be necessary. The main advantages of using Orbiter hardware include (1) significant savings in DDT&E costs and (2) reduced program risk by the use of proven designs.

It should be noted that Orbiter design requirements are different from those for the SCB. When the performance requirements for SCB differ from those for Orbiter, the hardware will be required to operate at off-design point conditions. These factors will probably result in weight and power penalties and the use of multiple units in those instances wherein a single unit does not possess sufficient capacity.

With specific regard to the use of Orbiter hardware, the degrees of applicability of the various STS subsystems appear to be as follows:

| Subsystem | % Applicable | Typical |
|---|---|---|
| • ECLSS | 40-50 | • Pressure control, tanks, heat exchangers and valves |
| • Electrical Power | 5-10 | • Inverters, switches and circuit breakers |
| • Crew Habitability | 65-75 | • EVA equip, food storage and preparation, and clothing |
| • Propulsion – RCS | 70-80 | • Fuel and oxidizer tanks, thrusters, valves, and pressurization system |
| • Guidance and Control | 40-50 | • RCS driver electronics, hand controllers and controls/displays |
| • Data Management and Communication | 75-80 | • Computer, MDM's, antenna, receivers, TV cameras, and signal conditioners |
| • RMS | 50 | • Technology |

| SUBSYSTEM | SELECTIONS |
|---|---|
| STRUCTURAL MECHANICAL | • ORBITER D-HATCH DOCKING MECHANISM<br>• 53 FT MAX LENGTH PRESSURE SHELL |
| ECLSS | • CLOSED WATER – OPEN $O_2$ WITH HS-C $CO_2$ CONTROL<br>• $O_2$ RECOVERY – DESIGN FOR RETROFIT |
| ELECTRIC POWER | • SOLAR ARRAY POWER SOURCE<br>• BATTERIES FOR ENERGY STORAGE |
| CREW HABITABILITY | • WHOLE BODY WASHING – ORBITER SPONGE BATH<br>• FOOD – ORBITER TYPE FREEZE DRIED, DEHYDRATED, THERMALLY STABILIZED |
| PROPULSION – RCS | • THRUSTERS – ORBITER 25 LBF VERNIER THRUSTERS<br>• COMPONENTS/PROPELLANT (MMH & $N_2O_4$), ORBITER TANKS, VALVES, AND CONTROLS |
| GUIDANCE AND CONTROL | • IMU's, STAR TRACKERS, AND HORIZON SENSORS<br>• INTERFACES WITH DATA MANAGEMENT SYSTEM IN ORBITER OR CS<br>• ATTITUDE CONTROL AND ORBIT KEEPING – RCS |
| DATA MANAGEMENT AND COMMUNICATION | • DISTRIBUTED DATA PROCESSING – ORBITER<br>• STANDARD TDRSS COMPATIBLE COMMUNICATIONS – ORBITER |
| CRANE | • 7 DEGREES OF FREEDOM – 2 ARMS/35M REACH<br>• TURRET CONTROLLED/ DIRECT VISIBILITY |

**Figure 35. Key SCB Subsystems Concepts**

Figure 35 summarizes the recommended concepts for each of the SCB subsystems. A feature of the structural/mechanical subsystem is the berthing mechanism, which can be converted on orbit to a docking mechanism if the need arises. The design concept for this was derived from earlier Space Station studies. The Orbiter docking mechanism, which uses existing designs and technology and is derived from the international docking mechanism, is used for ports exclusively dedicated to docking.

A closed water – open $O_2$ ECLSS design is recommended for initial versions of the SCB due to its lower initial cost. Capability to retrofit for closed oxygen is incorporated in the initial open design to reduce logistics needs later in the program.

Solar arrays for power source and batteries for energy storage are recommended for the electrical power system because this design uses proven technology and, therefore, represents minimum program risk.

Crew habitability provisions are compatible with an austere construction shack philosophy. Sponge bathing and Orbiter-type food are proposed. Maximum use is made of existing Orbiter hardware such as clothing, food, personal hygiene facilities and EVA equipment.

The recommended propulsion subsystem makes use of existing Orbiter hardware which will save significant DDT&E costs. This bipropellant con-

cept is not as efficient or as contaminant free as an advanced $H_2$-$O_2$ system, but represents an acceptable concept, due to the remote boom mounting, and uses existing proven technology.

The IMU in the guidance and control subsystem provides the basic attitude reference for control logic. It would be supported by star tracker references and the navigation ephemerides for accuracy update for a wide variety of desired orbital reference orientations. The distribution data processing is also Orbiter hardware.

A seven-degree-of-freedom (or eight-degree-of-freedom if rotation of the base is considered) two-arm crane with a 35m reach is required to accomplish construction and vehicle movement tasks.

**HOW DO THE SHUTTLE, THE SPACELAB, AND THE SPACE CONSTRUCTION BASE ELEMENTS RELATE IN A LOGICAL AND EVOLUTIONARY PLAN?**

An evolutionary space program must follow a logical and orderly transition from the initial Shuttle/Spacelab capability to longer-duration Shuttle-tended operations and finally to facilities permitting continuous operations in various orbital regimes.

Expendable launch vehicles will be phased out as the Shuttle becomes operational; as a result, the Shuttle Orbiter will be the logistics workhorse of space for many years to come (Figure 36). With regard to Spacelab, a review of currently proposed NASA mission models and other related mission-planning materials indicates that significant research and development work will be accomplished during STS-Spacelab missions programmed for the 1980 to 1983 time period in the areas of space processing, life sciences, physics and astronomy, earth sciences, and space technology. R&D efforts in construction-related technologies also can be accomplished during this period. The experience and data from these earlier efforts will provide the point of departure for the missions to be defined for the time period beyond 1983.

Furthermore, it can be anticipated that the Spacelab system will continue to be useful for missions and support operations after 1983. This is not only true

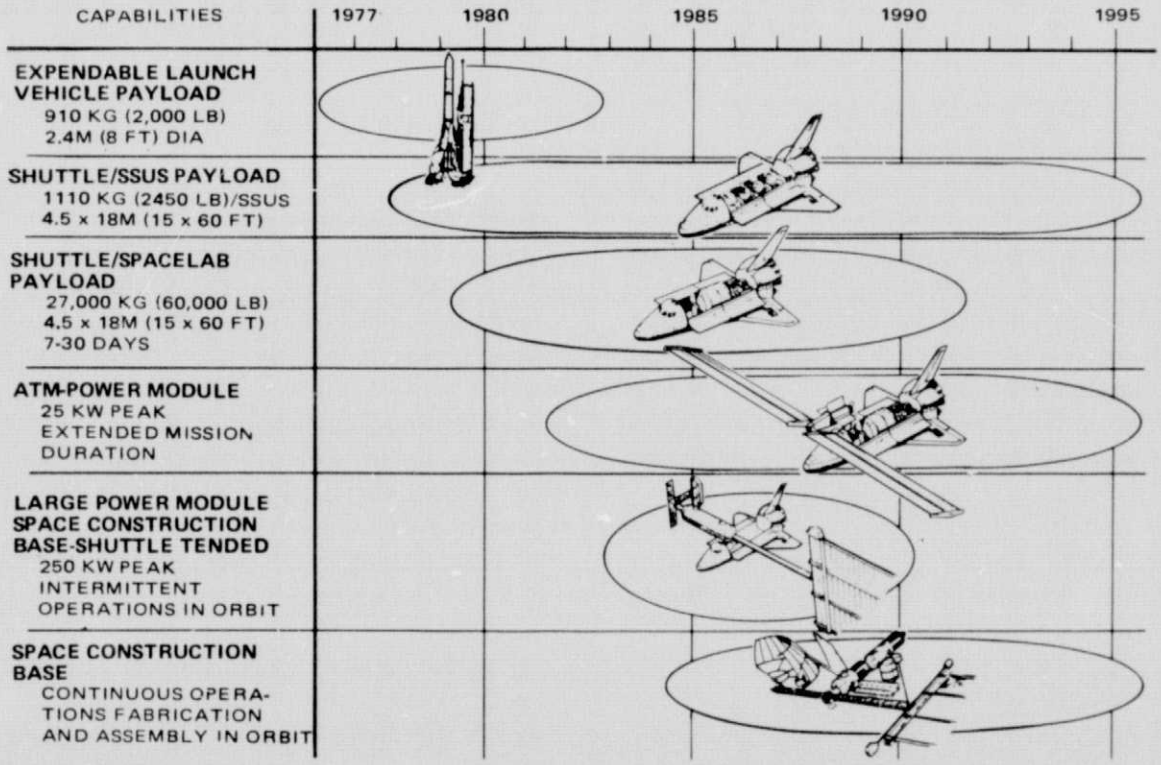


**Figure 36. Space Program Evolution**

of the support hardware (modules, pallets, etc.), but also of much of the planned mission hardware. For example, solar astronomy instruments may be beneficially employed in continuous operations for an indefinite period. As currently conceived, the small power module is primarily intended to extend the capability of the Orbiter/Spacelab. When combined with construction equipment, resulting in the Shuttle-tended construction base, the power module can continue to support the Orbiter/Spacelab on an alternate mission basis.

As previously discussed, when the "Construction Shack" (habitability module) is added to create a capability for continuous operations, Spacelab can be directly attached to the construction base. In this case, the construction base replaces the Orbiter in supporting Spacelab, and simultaneous construction and laboratory missions may be undertaken. With addition of the large power module, the initial small module is free to support independent Orbiter/Spacelab missions. Thus, Spacelab usefulness is enhanced and continued use of this valuable asset is ensured.

Figure 37 summarizes the mission durations, payload weight, crew sizes, power, orbital regimes, and manhours per year, which can be anticipated for the basic Shuttle-Spacelab system, and for the Space Construction Base (SCB). Areas of capability overlap are also indicated. The final program plan developed for the 1980's must achieve an optimal balance of the potential capabilities which will be available.

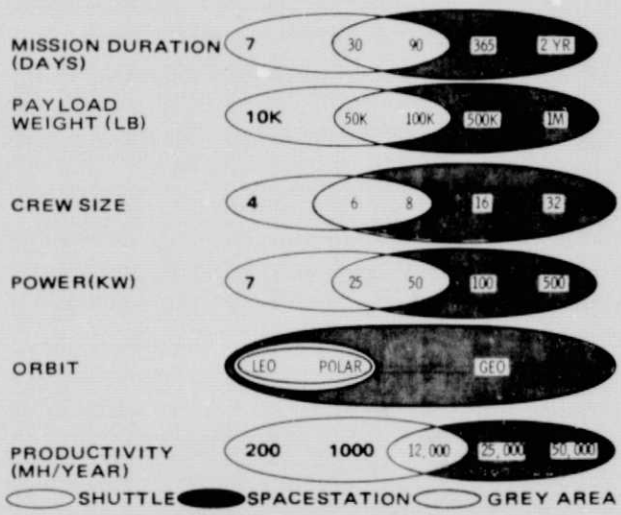


**Figure 37. Shuttle/Space Station Operating Regimes**

The boundaries of the transition zone between extended-duration Shuttle capabilities and those which are better provided by a permanent, continuously manned space platform will be largely dependent upon the specific missions to be accomplished and the allowable rate of funding expenditure.

A critical issue of the study has involved considerations of which of the activities required by the key objectives should be accomplished in a short duration 7-day sortie mode, which should be done in a longer duration 7-to-30-day Shuttle-tended mode, and when does it make sense to go to a continuous operations mode.

One of the most critical aspects of this issue is the time it takes to do the job at hand. Total time estimates were based on process times, contingency allowances, and checkout times. With these estimates, it was determined that a minimum of 30 to 40 days would be required for many of the construction jobs. When test program requirements are added, other construction tasks may take over a year. Some activities such as the space science missions and space processing also require long uninterrupted periods in zero-g conditions.

Assuming a maximum 30-day Shuttle on-orbit capability, the on-orbit requirements for various construction items were assessed relative to the Shuttle's capability and are summarized in Figure 38. It was found that several items are not compatible with a single Shuttle flight because more than one flight is needed to deliver hardware. The support of others was doubtful due to such things as RMS reach capabilities and orbit stay time. This investigation revealed that, of the mission hardware items considered, only construction of the power platform and TA-1 appear to be compatible with a single shuttle mode of operation, though for TA-1, 270 days of sortie missions would subsequently be required to support the experimental test program. Multiple sorties can accommodate construction of additional mission hardware items, while a Shuttle-tended space construction module can support all of the construction tasks.

| CONSTRUCTION ITEM | PAYLOAD WEIGHT/ VOLUME | TIME | POWER | MANIP-ULATOR | EQUIP/ MENT TOOL INSTALL-ATION | COMPATIBLE MODES | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | SINGLE SORTIE | MULTI-PLE SORTIE | SHUTTLE TENDED SCM |
| TA-1 DEPLOY/ASSEMBLY | | | | | | ✓ | ✓ | ✓ |
| TA-1 FABRICATION AUTO ASSEMBLY | | | | | | | | ✓ |
| TA-2 DEPLOY/ASSEMBLY | | | | | | | ✓ | ✓ |
| TA-2 FABRICATION AUTO ASSEMBLY | | | | | | | | ✓ |
| MBL ASSEMBLY | | | | | | | | ✓ |
| 30M RADIOMETER ASSEMBLY | | | | | | | | ✓ |
| 100M RADIOMETER ASSEMBLY | | | | | | | | ✓ |
| POWER PLATFORM DEPLOY | | | | | | | ✓ | ✓ |
| POWER PLATFORM ASSEMBLY | | | | | | ✓ | ✓ | ✓ |
| POWER PLATFORM FABRICATION | | | | | | ✓ | ✓ | ✓ |
| POWER PLATFORM FAB-RICATION AUTO ASSEMBLY | | | | | | | | ✓ |

*ASSUMES 30-DAY SHUTTLE

GENERALLY COMPATIBLE | MARGINAL | GENERALLY NOT COMPATIBLE

**Figure 38. Sortie Mode/Construction Requirements Compatibility***

As an example of sortie mode vs Shuttle-tended operation, the power platform (in the fabrication mode) exhibits compatibility with the sortie mode of operation. (See Figure 39.) The 100m radiometer is an example of an item that is not compatible. The 100m radiometer requires six shuttle launches, about 6 months to construct, and a manipulator/ tooling combination which allow working in a 50m envelope.

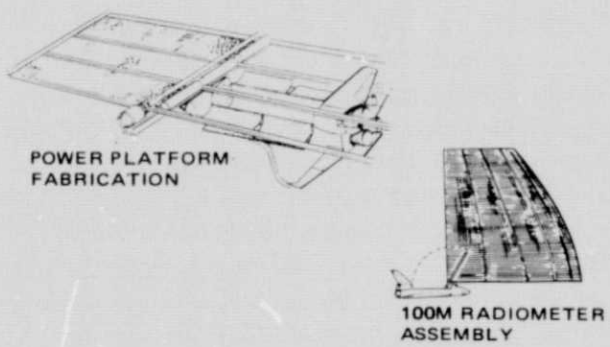


**Figure 39. Sortie Mode Configuration**

In comparing the Shuttle-tended with the continuous operations mode, another primary consideration is the cost of transportation. (See Figure 40). An analysis of the costs involved, considering the previously discussed construction time spans, was made. In this analysis it was recognized that hardware delivery flights also can be used as crew operation flights in the Shuttle-tended mode. As a result, some activities exhibit large cost savings in the continuous operations mode while others, where the number of flights is compatible with the time required, show no savings. If experimental test times are included (TA-2 requires a 1-year test program), the cost savings of continuous operations becomes significant.

In terms of the logical development of an evolutionary program (Figure 41), it is proposed that after the basic construction related technology development flights have been undertaken, the first step should be to provide an increase in available on-orbit electrical power by means of an additional power module. This step, which is necessary to support Spacelab missions could

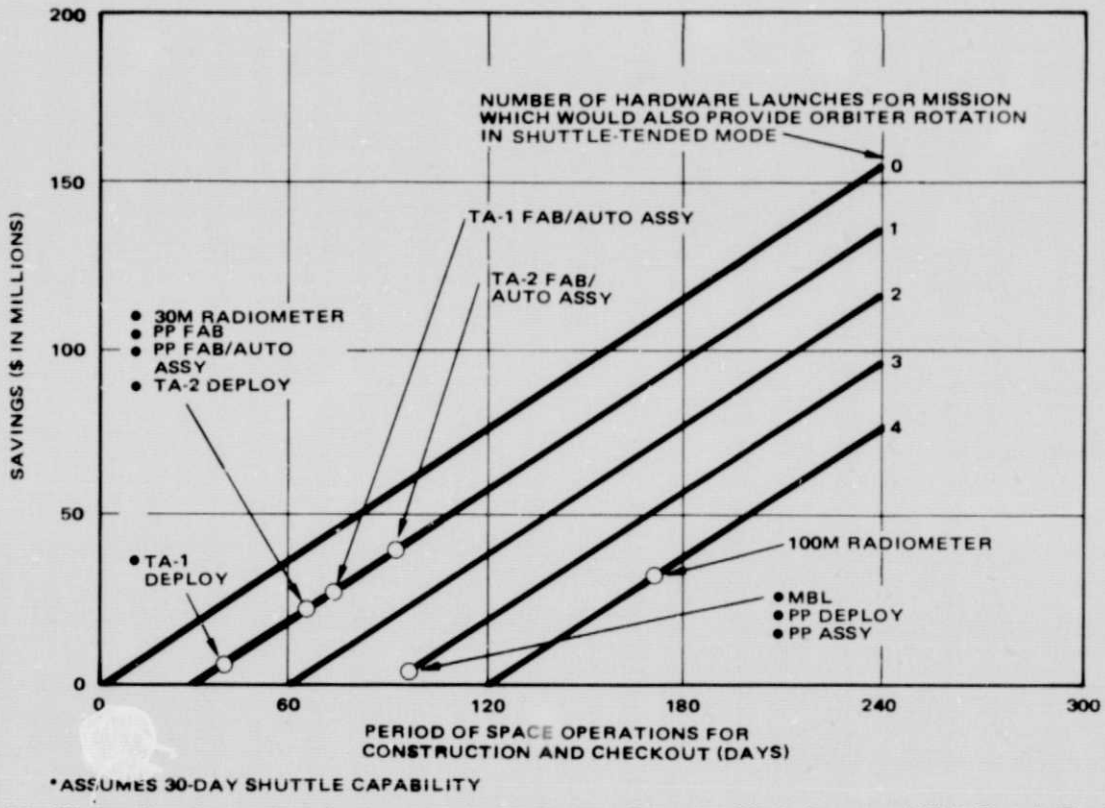


Figure 40. Mission Cost Savings For Construction in Continuous Operation Mode Compared With Shuttle-Tended*

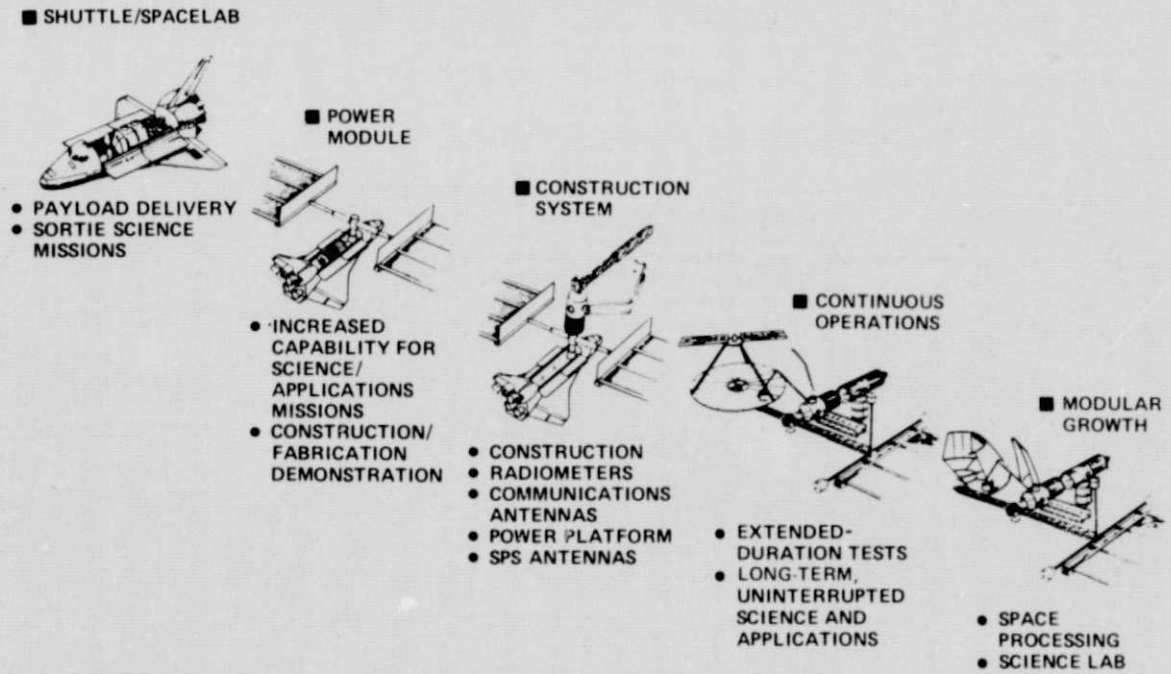


Figure 41. Evolutionary Space Program

support early activities associated with SPS and earth services objective elements and science and/or space processing research missions. At this point in the program, the introduction of the space construction module as the second key element in the evolving capability would provide in a Shuttle-tended mode the first significant operational capability to construct or assemble new items of mission hardware.

As the complexity and sizes of the objective elements increase, increased on-orbit durations and extended capabilities will be required and the addition of a construction shack as the third key element in the evolutionary program will be necessary to provide habitation functions outside of the orbiter. Another key element would be a large power platform, 250 kW, to provide increased supplies of electrical energy. These last two evolutionary steps would advance the autonomy of the Space Construction Base to the point where continuous operations could be available to keep pace with the expanding workloads. Other objectives such as the initial space processing research, space sciences, etc could be supported as well as the conduct of SPS development tests. The next advance in capability would involve continuous support of commercial space processing production development, multipurpose science missions, large scale construction and productivity demonstrations, and development of the capability to conduct manned operations at GEO.

Throughout the steps of the program, the pace and order of introduction of the elements of the SCB involve trades of timely cost avoidance alternatives versus longer range system options which, though more costly initially, quickly result in less costly and more efficient operations, thus reducing total program runout costs.

## WHAT MILESTONES, SCHEDULES AND COSTS APPEAR REASONABLE?

Based upon the analyses conducted during the study, an evolutionary program providing increasing capability with time was developed as the recommended baseline. (See Figure 42.) As outlined above, this program starts with technology development activities which use only the Shuttle and Spacelab. As additional resources become available, more extensive orbital activities are introduced, including construction demonstrations and extended duration missions. Eventually, a further uprating of the orbital Space Construction Base will be required to support very large scale activities such as commercial space processing plants, prototype size SPS pilot plant construction, multi-module science activities, and geosynchronous operations.

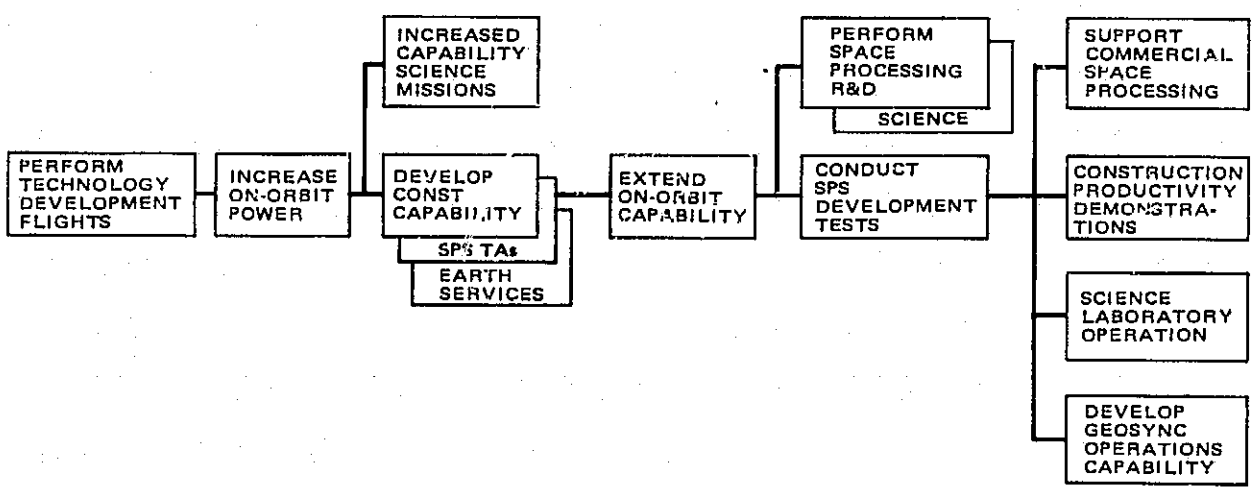


Figure 42. Evolutionary Program

Figure 43 shows the schedule for the principal activities of the baseline program from the start of DDT&E through the completion of each activity. The triangle symbols indicate the operational date for the hardware that is required to support each activity. For example, the SPS Test Article 1 (TA-1) activity requires a Low Earth Orbit antenna (LEO), two Beam Mapping Satellites (BMS), and a Geosynchronous free-flying antenna (GEO). The Shuttle is used for all orbital activities up to early 1984 when the Construction Shack is placed in orbit. The Construction Shack is suggested for launch at this time because analysis indicated that early continuous manning capability would lower the total program cost by $300 million (10%) compared to continuing the Shuttle-tended mode of operation through 1985.

Figure 44 presents the cost of development, production, transportation to orbit, and operations for the Space Construction Base elements of the program and for the Mission Hardware as defined to date. The cost of each of the hardware elements is indicated on the bar along with the total cost for transport and operations. The cumulative funding over the period up until the last of the SCB hardware elements is operational is also indicated. These data assume the Construction Shack is operational in early 1984. The effect of delaying its introduction until later (as indicated by the phantom triangle in Figure 43) would be to reduce the early year funding (DDT&E) by $170 million, but later year funding would be increased as noted above due to the increase in transportation costs associated with the Shuttle-tended mode of operation. From a total program cost standpoint, the net result would be a slightly higher total cost for later introduction of the Construction Shack.

The cost (Figure 44) estimated for mission hardware include the development, production, transport to orbit and operation through the year 1988. The bar indicates the cost of each individual item. The cumulative funding over the period of interest is also indicated on the figure. It should be noted that some of the more ambitious mission hardware such as the dedicated space processing modules and manned geosynchronous operations were not included since they fall outside the time period indicated.

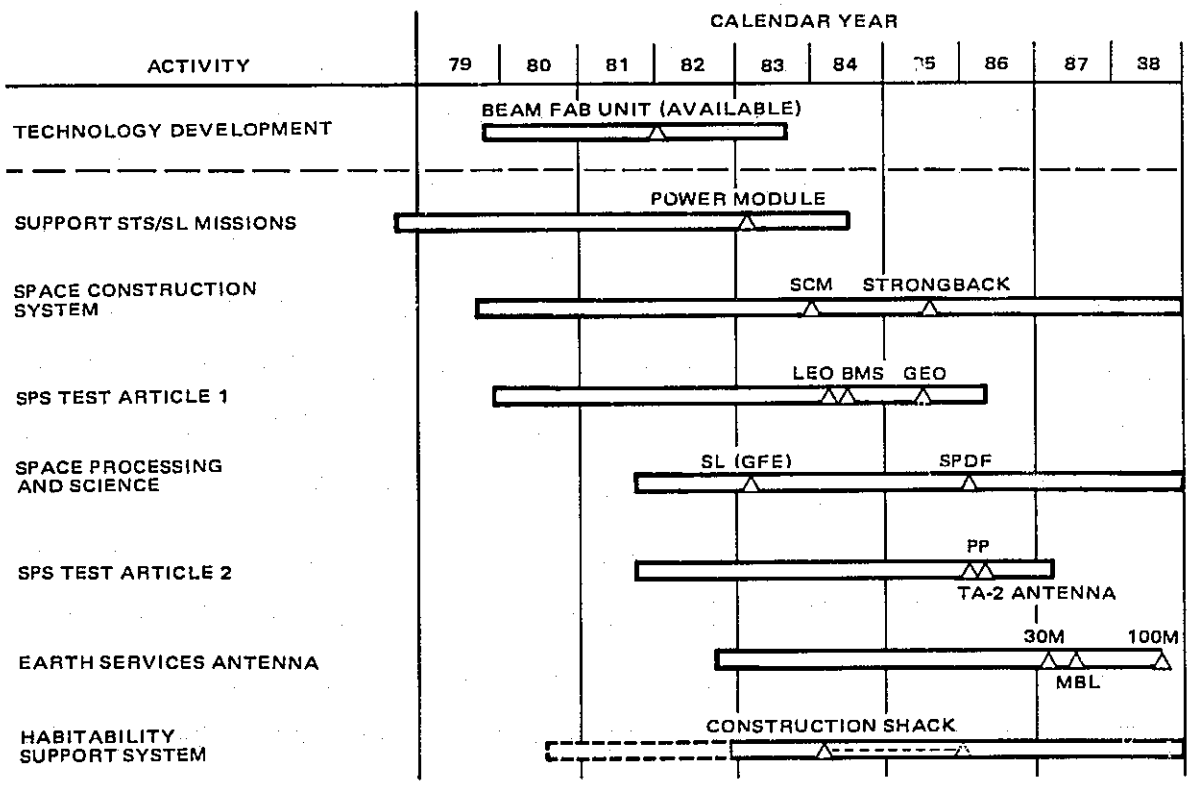


**Figure 43. Baseline Program Schedule**

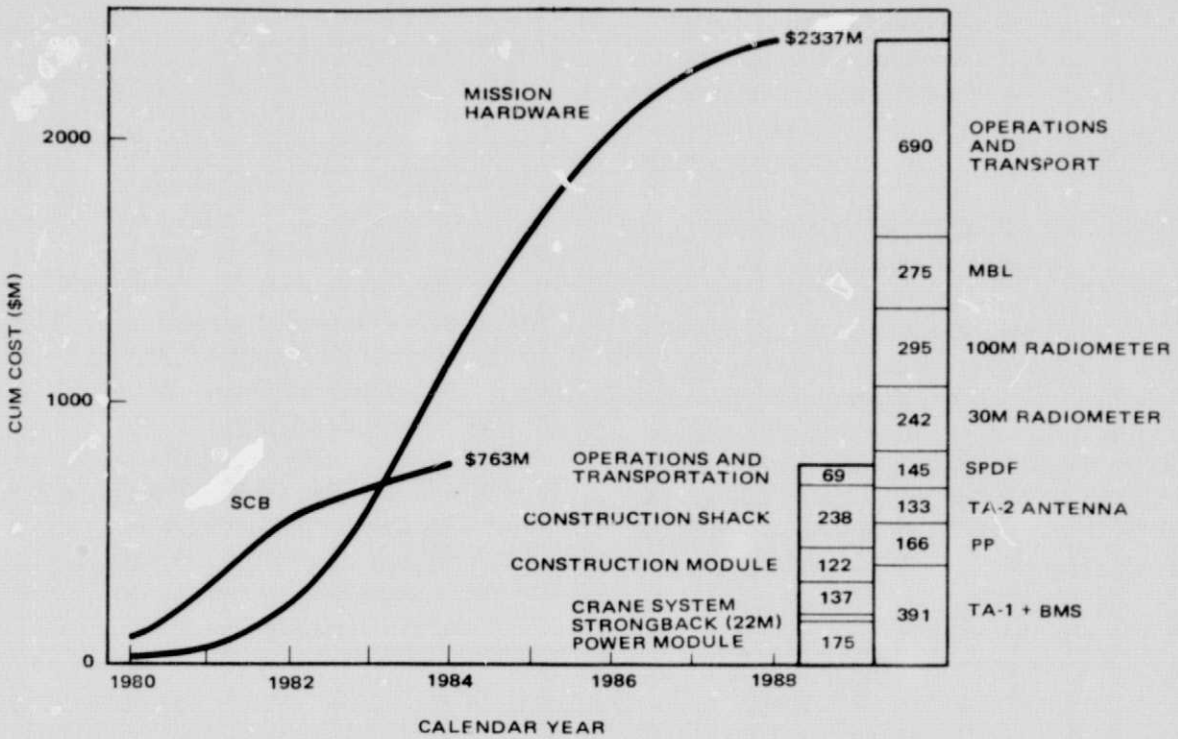


**Figure 44. DDT&E, Production, Operations, and Transport Costs**

When these cost figures are plotted against the projection of a constant NASA budget level of 4 billion 1977 dollars (Figure 45), it would appear that the development of the space construction base concept in the mid 1980s is well within the projected budgetary constraints anticipated at this time. The SCB concept represents a viable and realizable goal.

With regard to technology issues and the requirements for supporting research, a primary finding of the Space Station Systems Analysis Study is that the design and operational requirements of the evolutionary SCB program are comfortably within the state-of-the-art. However, several systems and technology areas, principally related to construction in space, should be examined in greater depth before a commitment is made to Phase C/D. These issues include such considerations for the space construction base as the development of construction system techniques including space crane technology. For potential mission hardware the issues include the investigation of the combined environmental effects on large space structures and the analysis of the dynamics and the development of optimization techniques for the control of those structures. In addition, mission hardware items for specific applications such as the multibeam lens antenna require further study, research and development. The plan to resolve these issues is documented in the Technical Volume of this report. The objective of this SRT is to provide high confidence solutions for the various developmental issues, within a time period compatible with the overall evolutionary SCB schedule.

## CONCLUDING COMMENT

The most significant conclusion reached during this study is that an evolutionary, carefully paced space station program fits within NASA's projected budget. There is a need for such a space station facility to provide the economies associated with long duration manned missions in earth orbit. The thematic orientation of such a system should be that of a space construction base. Such a facility can and will develop as an evolutionary program wherein each of the steps, while providing significant capabilities in their own right, also are building blocks for future growth. Thus, a long term commitment to a specific end system is not necessary at this time but rather the operational systems of the future will be products of the developments and experiences of a continually evolving program.

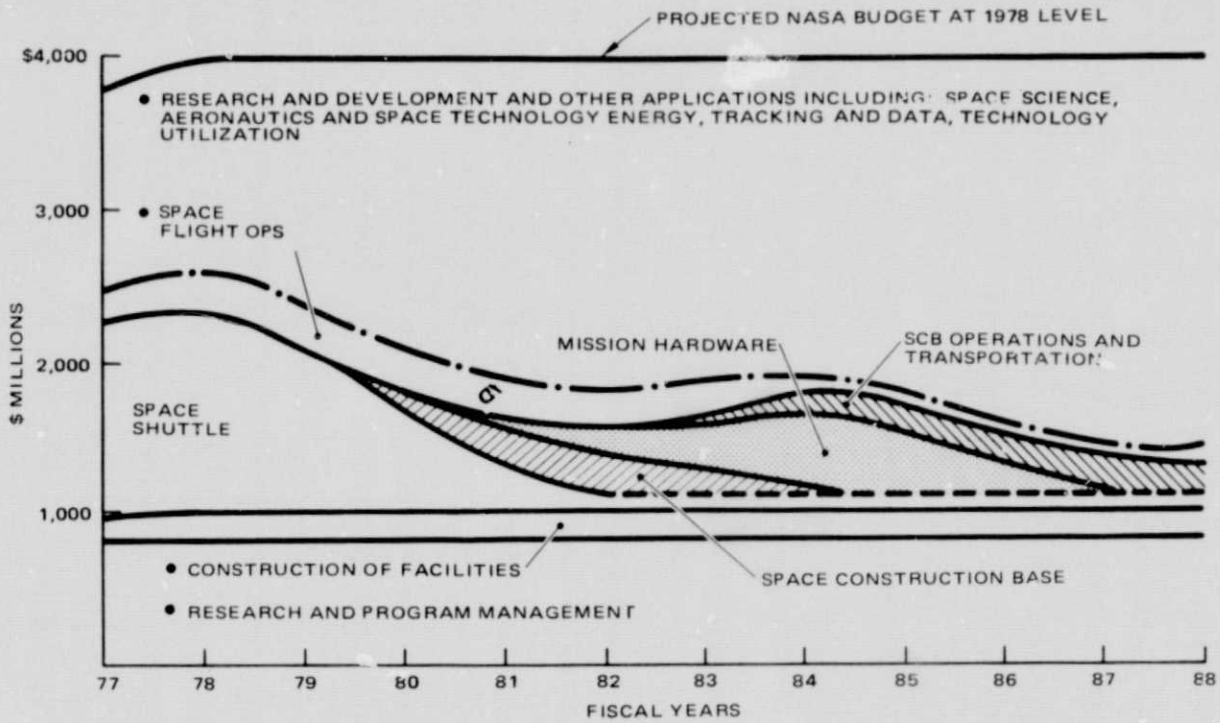


**Figure 45. Space Construction Base Funding is Compatible with Constant NASA Budget**

In extending the current Shuttle Spacelab capabilities the first step should be the development of a power module capable of being left in orbit to service the needs of repeat Shuttle and Shuttle Spacelab operations. Such a unit could in turn support free-flying Spacelabs and space construction modules as the requirements of future missions dictate and as these additional facilities are developed. While initial growth will be predicated upon Shuttle-tended operations, as the building blocks become available, the continuously manned construction base will naturally evolve.

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This photograph, courtesy of the Hale Observatories, shows the Great Galaxy in Andromeda as viewed through stars in our Galaxy from a ground based 100 inch telescope. This Galaxy composed of millions of stars is over a million light years from our own system. A large 3 meter telescope in space unobscured by the Earth's atmosphere could detect objects of this size at a distance of ten billion light years, a distance beyond the limits of the Universe as we now know it.

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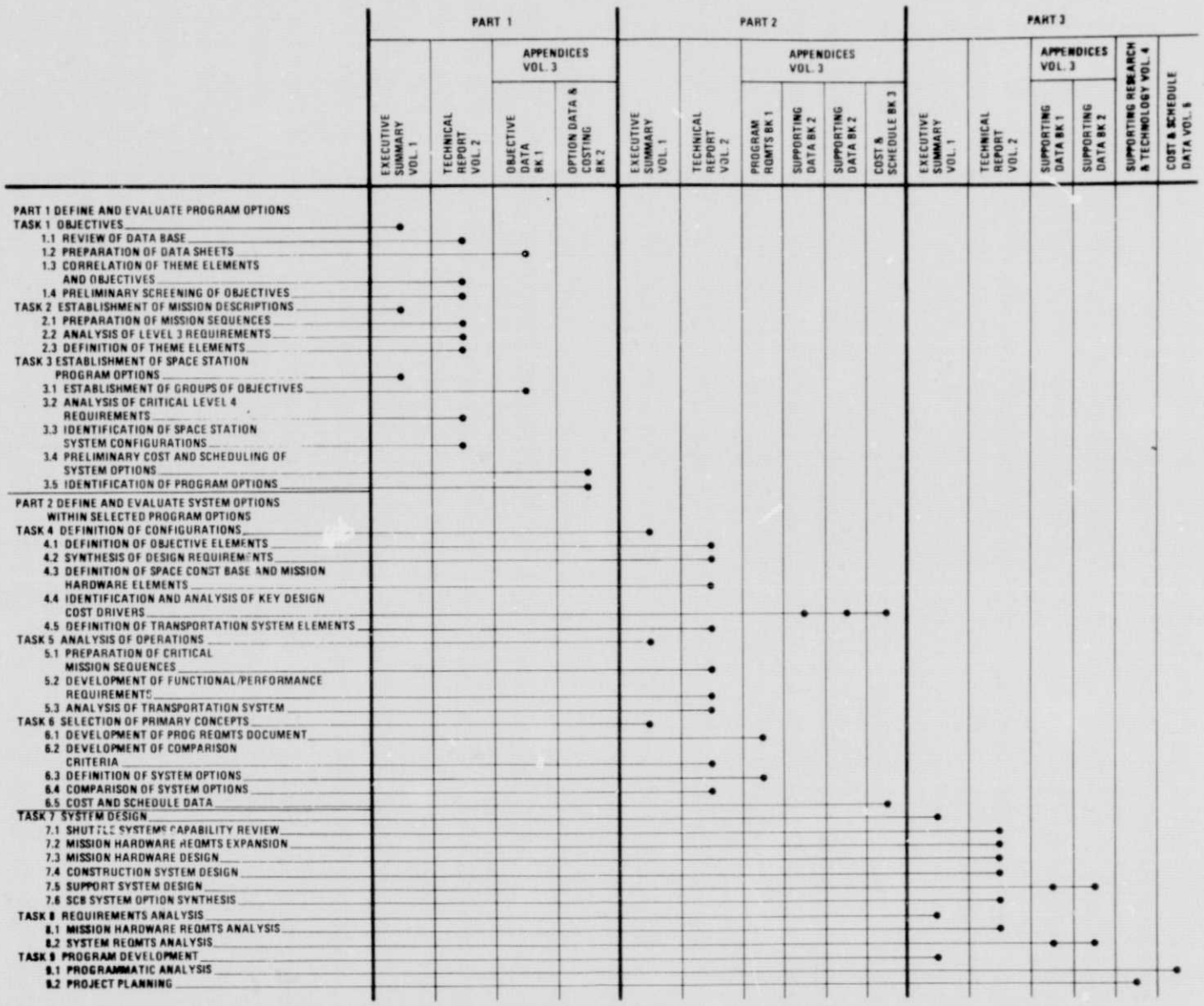
## Subject Reference Matrix

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